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# 1 ACTIVE NEEDLE DEVICES WITH INTEGRATED FUNCTIONALITY

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

5 The present invention relates generally to needle devices for the injection and extraction of fluids. More specifically, the present invention relates to active needle devices such as macroneedles, microneedles, and macroneedle or microneedle arrays which have one or more active components providing additional functionality to the needle devices.

### 10 2. Relevant Technology

Micro instrumentation is a rapidly growing area of interest for a broad spectrum of applications. One particularly fast growing area is biomedical instrumentation where significant efforts are being made to develop micro biochemical analysis systems, physiological analysis systems, and drug delivery systems. A variety of manufacturing technologies are used to fabricate these micro systems, many of which are categorized under the set of technologies known as micromachining. The number of biomedical applications for micromachining technologies is rapidly growing. Since micromachining technologies are relatively new, there is an increasing set of manufacturing techniques and critical applications still to be addressed.

20 It is well known that needles are used to extract samples of substances from living tissue in order to analyze the substances for diagnostic purposes, or to deliver a drug or medicament. The majority of needles in use today are macroneedles, which have a relatively large diameter as compared to a blood cell and are on the order of millimeters (mm).

25 In many areas of biotechnology and medicine, there exists the need for fluid injection or extraction on a microscale; either for injection into a precise location, or for injecting or extracting small amounts of fluid. It is advantageous to be able to perform these injections or extractions with a minimal amount of tissue damage, and also with a minimum amount of discomfort and pain to patients. Microneedles and microneedle arrays are capable of performing these tasks. For example, microneedles and microneedle arrays can be used as precise injection/extraction needles in cell biology, as injection/extraction heads in a drug delivery system or microchemical

30

1 factory, and as injection/extraction heads in microsurgery. Some of the smallest  
hollow needles that are currently available have inner diameters of over 200  $\mu\text{m}$ .  
Prior micro-sized (sizes on the order of microns, where 1 micron = 1  $\mu\text{m}$  =  $10^{-6}\text{m}$ )  
5 needles include those disclosed in U.S. Patent No. 5,457,041 to Ginaven et al., and  
U.S. Patent No. 5,591,139 to Lin et al.

For some applications, it is desirable to inject small amounts of fluid;  
however, in other situations, larger amounts of fluid are required to be injected. Most  
of the prior systems do not have the capability to transmit larger amounts of fluid into  
10 a precise location. One of the methods used to address this problem is to fabricate an  
array of needles, as in U.S. Patent No. 5,457,041 referred to hereinabove, which  
discloses an array of microneedles of about 20 needles by 20 needles, wherein the  
length of the needles is between 10 and 25 microns, and the spacing between needles  
is between about 5 and 20 microns.

15 In U.S. Patent No. 5,591,139 referred to above, silicon-based microneedles are  
disclosed which are fabricated using integrated circuit processes. Various devices  
such as microheaters, microdetectors, and other devices can be fabricated on the  
microneedle.

Problems with prior microneedles include relatively poor mechanical  
20 durability. This is mainly due to the fact that such microneedles have been made out  
of etched silicon or out of chemical vapor deposited polysilicon, both of which have a  
tendency to be brittle and break easily.

In some cases, it is desirable to analyze the fluids being injected or extracted  
by the microneedle(s). Prior microneedles generally have been separate from the  
25 systems used to analyze (chemically, optically, or otherwise) the fluids. In these  
cases, having a separate analysis system can require additional equipment and is  
costly, complex, and inconvenient.

It would therefore be of substantial interest to develop a durable needle device  
which is capable of injecting or extracting precise quantities of fluids into specific  
30 locations with a minimal amount of tissue damage, and which has integrated sensing  
capabilities.

### **SUMMARY OF THE INVENTION**

Active needle devices of the present invention have integrated functionalities

1 such as biochemical, electrical, or optical sensing capabilities. The active needle devices can be active macroneedles or microneedles, as well as active macroneedle or microneedle arrays, which incorporate biosensors therein such as for monitoring metabolic levels.

5 In one embodiment of the invention, an active needle device for fluid injection or extraction includes at least one hollow elongated shaft defining at least one channel therethrough. The channel provides communication between at least one input port and at least one output port of the needle device. At least one active component such as a sensor or actuator is placed or integrated into the elongated shaft. The needle device can be a macroneedle, a microneedle, or an array of macroneedles or microneedles. The microneedles can be fabricated on a substrate which can remain attached to the microneedles or can be subsequently removed. The active component can facilitate biochemical, optical, electrical, or physical measurements of a fluid injected or extracted by the needle device.

15 Two- or three-dimensional microneedle arrays can be constructed having cross-coupling flow channels that allow for pressure equalization, and balance of fluid flow within the microneedle arrays. A plurality of mechanical support members can be integrated into the arrays for stability and to control the penetration depth of the microneedles. In addition, an active microneedle or microneedle array may include various functionalities such as integrated biochemical sensors, as well as electrical, optical, or mechanical transducers and sensors. The sensors reduce or eliminate the requirement for additional external analysis equipment and enhance overall device portability, disposability, and compactness.

25 The active microneedle and microneedle arrays of the invention are particularly useful for fluid extraction and analysis. In one embodiment, an active microneedle or microneedle array includes biochemical sensing reagents which are deposited on an inner surface of the microneedle(s), with a window provided on a surface of the microneedle(s) for the detection of bioluminescence which occurs in the presence of certain metabolic substances.

30 A method of fabricating an active microneedle device according to the present invention includes providing a substrate with a substantially planar surface and depositing a metal material on the planar surface to form one or more bottom walls

1 for one or more microneedles. A top surface of the bottom walls is coated with a  
photoresist layer to a height corresponding to a selected inner height of a  
microchannel for each of the microneedles. A metal material is then deposited to  
5 form side walls and a top wall upon the bottom walls and around the photoresist layer.  
The photoresist layer is then removed from each microchannel to form the  
microneedles. The microneedles can be released from the substrate and used  
independently of the substrate, if desired.

The method of fabricating the active microneedle device can include  $p^+$  etch-  
stop membrane technology, anisotropic etching of silicon in potassium hydroxide,  
10 sacrificial thick photoresist micromolding technology, and micro-electrodeposition  
technology. For a biochemical luminescence sensing microneedle device, certain  
biochemical sensing reagents can be drawn into and dried onto the inner walls of the  
hollow needle(s).

The active needle devices of the invention have the advantage of permitting  
15 real-time analysis of a fluid being sampled. In addition, the array of active  
microneedles are capable of injecting or extracting relatively large quantities of fluids  
with minimal tissue damage and can be readily attached to a standard syringe. The  
array of active microneedles or a single active microneedle can also be easily and  
economically fabricated. Yet another advantage of the array of active microneedles  
20 or a single active microneedle is a high degree of mechanical durability.

These and other features of the present invention will become more fully  
apparent from the following description, or may be learned by the practice of the  
invention as set forth hereinafter.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

25 In order to more fully understand the manner in which the above recited and  
other advantages of the invention are obtained, a more particular description of the  
invention briefly described above will be rendered by reference to specific  
embodiments thereof which are illustrated in the appended drawings. Understanding  
that these drawings depict only typical embodiments of the invention and are not  
30 therefore to be considered limiting of its scope, the invention will be described and  
explained with additional specificity and detail through the use of the accompanying  
drawings in which:



1       Figure 1A is a schematic representation of a single active needle device according to the present invention;

5       Figure 1B is a schematic representation of a portion of a single active needle device in the form of a microneedle according to one embodiment of the present invention;

      Figures 2A and 2B are schematic depictions of multi-lumen active microneedles according to alternative embodiments of the present invention;

      Figure 3 is a schematic representation of microneedles in a two-dimensional array according to a further embodiment of the present invention;

10       Figure 4 is a schematic representation of microneedles in a two-dimensional array according to another embodiment of the present invention;

      Figure 5 is a schematic representation of microneedles in a two-dimensional array according to another embodiment of the present invention;

15       Figures 6A-6B are schematic depictions of single-lumen active microneedle arrays according to alternative embodiments of the present invention;

      Figures 7A-7B are schematic depictions of multi-lumen active microneedle arrays according to alternative embodiments of the present invention;

      Figures 8A-8F schematically depict the fabrication process sequence for forming a microneedle array;

20       Figure 8G depicts an embodiment of a multilumen microneedle formed according to the present invention;

      Figures 9A and 9B depict alternative methods of assembling two-dimensional needle arrays into three-dimensional needle array devices;

25       Figure 10 is a schematic depiction of a pressure sensor in an active microneedle according to the invention;

      Figure 11 is a graph of the normalized bioluminescent signal as a function of glucose concentration;

      Figure 12 is a graph of the normalized bioluminescent signal as a function of time for several different concentrations of creatine;

30       Figure 13 is a graph of the normalized bioluminescent signal as a function of creatine concentration; and

      Figure 14 is a graph of the average CCD counts as a function of volume for

1 different sample volumes.

### DETAILED DESCRIPTION OF THE INVENTION

5 The present invention is directed to active needle devices, such as macroneedles, microneedles, and macroneedle or microneedle arrays, which have one or more active components incorporated therein providing additional functionality to the needle devices. An active needle device according to the invention generally includes at least one hollow elongated shaft defining at least one channel therethrough. The channel provides communication between at least one input port and at least one output port of the needle device. At least one active component such as a sensor or actuator is placed or integrated into the elongated shaft. The active component can facilitate biochemical, optical, electrical, or physical measurements of a fluid injected or extracted by the needle device. The active component also reduces or eliminates the requirement for additional external analysis equipment, and enhances the overall device portability, disposability, and compactness.

15 Referring to the drawings, wherein like structures are provided with like reference designations, Figure 1A is a schematic representation of a single active needle device 10 according to one embodiment of the present invention. The needle device 10 includes a hollow elongated shaft 11 defining a single channel 12 from a proximal inlet end 13 to a distal tip end 14 which is tapered. One or more input ports 15 are located at the proximal inlet end 13 of elongated shaft 11 and one or more output ports 16 are located toward the distal tip end 14. The channel 12 provides communication between input ports 15 and output ports 16.

25 The needle device 10 can be either a macroneedle or a microneedle, depending on the configuration of elongated shaft 11 defining channel 12. A "macroneedle" as used herein means any conventional type needle used to inject or extract fluids, such as conventional metallic needles used in medical applications. A "microneedle" as used herein means any micro-sized needle which can be generally fabricated by micromachining techniques.

30 At least one active component 17 is placed or integrated directly in elongated shaft 11. The active component 17 can include one or more electronic components, electromechanical components, mechanical components, biochemical components, or various combinations thereof. These components can be configured to form one or

1 more sensors, actuators, or combinations thereof. For example, the sensors can be a  
biosensor, such as a bioluminescence-based biosensor, which is discussed in further  
detail hereafter, microdetectors, optical pressure sensors, DNA analyzer chips, and the  
like. The actuators can include electromechanical components for fluid manipulation  
5 such as micropumps, microvalves, or the like. In addition, active component 17 can  
include an integrated circuit chip, an optical detector, other electrical based  
components, impedance analyzers (e.g., integrated resistance, inductance, and  
capacitance sensors), transducers, and the like. A transducer can be used for detection  
of fluid parameters such as flow velocity, temperature, pressure, etc. The active  
10 component 17 can facilitate one or more biochemical, optical, electrical, or physical  
measurements or other analyzing functions for a fluid injected or extracted by needle  
device 10.

The active component 17 can be interfaced electronically with conventional  
analyzing equipment or can be a stand alone device. In addition, the active  
15 component 17 may be fabricated independently of the needle device and subsequently  
placed therein, or may in some cases be fabricated at the same time as the needle  
device. If fabricated independently, the active component can be made on separate  
chips, which can be affixed to an internal surface of the needle or substituted for part  
of a wall of the needle. Additional details related to active component 17, including  
20 specific embodiments thereof, are discussed below.

The active component 17 allows the needle device to provide real-time  
analysis of a fluid being sampled such as in a blood analysis system. For example,  
blood can be analyzed by an on-chip amplifier, such as a blood analysis amplifier, and  
an A/D converter which converts an analog signal to a digital signal for transmission  
25 to a computer for real-time computer analysis.

When needle device 10 is configured as a single microneedle, elongated shaft  
11 generally includes a bottom wall formed by a solid layer 19, and opposing side  
walls connected by a top wall which are formed by a hollow layer 20, as shown in  
Figure 1B. These bottom, side, and top walls define channel 12 in the form of a  
30 microchannel with a transverse cross-sectional profile that is substantially rectangular.  
The microneedle optionally has a flange 18 at proximal inlet end 13 (Figure 1A)  
which functions as a structural support for the microneedle. The flange 18 can control

1 penetration depth and can be used to mechanically fix the microneedle to a surface  
that is penetrated. The input ports 15 located at proximal inlet end 13 and output  
ports 16 are formed in one or more of the bottom wall, side walls, or top wall of the  
microneedle. The input ports 15 and output ports 16 in the microneedle can be  
5 formed by conventional fabrication processes such as etching. Figure 1B shows  
active component 17 such as a biosensor adjacent to output ports 16.

The microneedle can be fabricated by micromachining techniques from a  
variety of metallic materials such as nickel, copper, gold, silver, platinum, palladium,  
titanium, chromium, alloys thereof, and the like, as well as other materials such as  
10 silicon, polysilicon, ceramics, glass, carbon black, plastics, composites thereof, etc.  
In one embodiment, the microneedle is fabricated from a non-silicon material such as  
any of the above metallic materials using the micromachining techniques discussed in  
further detail below. The microneedle can be fixed on a substrate where fabricated or  
can be removed from a substrate after fabrication.

15 Figures 2A and 2B are schematic depictions of multi-lumen active  
microneedles according to alternative embodiments of the present invention. Figure  
2A illustrates a dual-lumen active microneedle 21 which is constructed in a similar  
manner as the microneedle of Figure 1B, having an elongated shaft 11 including a  
bottom wall formed by a solid layer 19, and opposing side walls connected by a top  
20 wall which are formed by a hollow layer 20. The hollow layer 20 is configured such  
that microneedle 21 has two microchannel members 22a and 22b each with a lumen  
therein and each with corresponding inputs 23a and 23b. One or more active  
components 17 such as biosensors are located in each of microchannel members 22a  
and 22b.

25 Figure 2B illustrates a tri-lumen active microneedle 24 which is constructed in  
a similar manner as microneedle 21. The microneedle 24 has an elongated shaft 11  
including a bottom wall formed by a solid layer 19, and opposing side walls  
connected by a top wall which are formed by a hollow layer 20. The hollow layer 20  
is configured such that microneedle 24 has three microchannel members 22a, 22b, and  
30 22c therein, each with corresponding inputs 23a, 23b, and 23c. One or more active  
components 17 such as biosensors are located in each of microchannel members 22a,  
22b, and 22c.

1       The multi-lumen active microneedles according to the present invention allow two or more different fluids to be delivered by the microneedle, which are mixed just before delivery. The multi-lumen active microneedles can also be used to separately distribute an extracted fluid for multiple analyses.

5       Figure 3 is a schematic depiction of an active microneedle array 25a according to another embodiment of the invention. The microneedle array 25a is formed in a two-dimensional configuration on a substrate 26 having a substantially planar upper surface 27. The substrate 26 is preferably composed of a semiconductor material such as silicon, although other materials can be employed such as glass,  
10       metals, ceramics, plastics, and composites or combinations thereof.

      A plurality of hollow microneedles 28 are formed on upper surface 27 of substrate 26. The microneedles 28 each have a bottom wall, two opposing side walls, and a top wall that define a microchannel therein. Each bottom wall is formed partially on upper surface 27 of substrate 26. The microneedles 28 each have one or  
15       more input ports 15 at a proximal end thereof. A distal portion of each microneedle 28 including the microchannels extends beyond an edge of upper surface 27 of substrate 26 in a cantilevered manner and terminates in needle tips 29 which can have a channel opening therein. In addition, one or more outlet ports 16 can be located adjacent to needle tips 29. The microneedles 28 are preferably aligned substantially  
20       parallel to each other on substrate 26. One or more active components 17, such as biosensors or other sensing or actuating devices as discussed above, are located in each of microneedles 28.

      The microchannels in the microneedles 28 are preferably dimensioned to have a width between sidewalls of less than about 100  $\mu\text{m}$ , and more preferably about 0  $\mu\text{m}$   
25       to about 50  $\mu\text{m}$ . When the width is zero between the sidewalls, the microneedles 28 effectively become one multilumen microneedle with a plurality of microchannels, as shown in Figures 2A and 2B. The height between the top and bottom walls of the microchannel is also preferably less than about 100  $\mu\text{m}$ , and more preferably about 2  $\mu\text{m}$  to about 50  $\mu\text{m}$ . The length of each microneedle can be from about 0.05  $\mu\text{m}$  to  
30       about 5 mm, and the width of each microneedle can be from about 0.05  $\mu\text{m}$  to about 1 mm. The center-to-center spacing between individual microneedles can be from about 50  $\mu\text{m}$  to about 200  $\mu\text{m}$ . The microneedles can also withstand flow rates of up

1 to about 1.5 cc/sec.

The microneedle length extended from substrate 26 can be varied from less than about 50  $\mu\text{m}$  (subcutaneous) to several millimeters for fluid delivery/extraction. For example, the distal end of each microneedle 28 can extend beyond the edge of  
5 substrate 26 a distance from about 10  $\mu\text{m}$  to about 100 mm. The inner cross-sectional dimensions of the microchannels in individual microneedles can range from about 10  $\mu\text{m}$  to about 1 mm in width and from about 2  $\mu\text{m}$  to about 50  $\mu\text{m}$  in height. Accordingly, the microchannel in each of the microneedles can have a cross-sectional area in the range from about 25  $\mu\text{m}^2$  to about 5000  $\mu\text{m}^2$ .  
10

A needle coupling channel member 30 can be optionally formed on upper surface 27 of substrate 26 between microneedles 28. The coupling channel member 30 has a bottom wall, two opposing side walls, and a top wall that define a coupling microchannel therein, which provides for fluid communication between the  
15 microchannels of each microneedle 28. The coupling channel member 30 also allows for pressure equalization and balance of fluid flow between microneedles 28.

Structural support members 31 can be formed on either side of coupling channel member 30 on upper surface 27 of substrate 26. The structural support members 31 mechanically interconnect microneedles 28 to provide rigidity and  
20 strength to microneedle array 25a. The support members 31 also precisely control the penetration depth of microneedles 28.

The microneedles 28, coupling channel member 30, and support members 31 can be formed from a variety of metal materials such as nickel, copper, gold, palladium, titanium, chromium, alloys or combinations thereof, and the like, as well  
25 as other materials such as silicon, polysilicon, ceramics, glass, carbon black, plastics, composites or combinations thereof, and the like. The microneedles 28 can be in fluid communication with a single fluid input device or with multiple fluid input devices (not shown).

An active microneedle array 25b according to an alternative embodiment of the invention is shown in Figure 4. The microneedle array 25b has a two-dimensional  
30 configuration with similar components as microneedle array 25a discussed above, except that the substrate has been removed from the array. Accordingly, microneedle array 25b includes a plurality of microneedles 32 with microchannels that are

1 dimensioned as discussed above for microneedle array 25a.

The microneedles 32 each terminate at a needle tip 33 with a channel opening 34 therein. A needle coupling channel member 36 with a coupling microchannel therein provides a fluidic interconnection between the microchannels of each  
5 microneedle 32. A pair of structural support members 38 are formed on either side of coupling channel member 36 and interconnect with microneedles 32. One or more input ports 37 and output ports 39 can be optionally formed in microneedles 32 to increase fluid input and output flow. The input ports 37 and output ports 39 can be  
10 formed in one or more of the bottom walls, side walls, or top walls of microneedles 32 by conventional fabrication processes such as etching. One or more active components 17, such as biosensors or other sensing or actuating devices as discussed above, are located in each of microneedles 32.

An active microneedle array 40 according to another embodiment of the invention is shown in Figure 5. The microneedle array 40 has a two-dimensional  
15 configuration with similar components as microneedle array 25b, except that microneedle array 40 is formed without a coupling channel member. Accordingly, microneedle array 40 includes a plurality of microneedles 32 with microchannels that are dimensioned as discussed above for microneedle array 25a. The microneedles 32 each terminate at a needle tip 33 with a channel opening 34 therein. A pair of  
20 structural support members 38 interconnect with microneedles 32. One or more input ports 37 and output ports 39 can be optionally formed in microneedles 32 to increase fluid input and output flow. One or more active components 17, such as biosensors or other sensing or actuating devices as discussed above, are located in each of microneedles 32.

25 Figures 6A-6B and 7A-7B are schematic depictions of single and multi-lumen active microneedle arrays according to alternative embodiments of the present invention. An active microneedle array 42a is shown in Figure 6A having a two-dimensional configuration with similar components as microneedle array 25b discussed above. Accordingly, microneedle array 42a includes a plurality of  
30 microneedles 32 each with single lumen microchannels 43. The microneedles 32 each terminate at a needle tip 33. A needle coupling channel member 36 with a coupling microchannel 44 therein provides a fluidic interconnection between

1 microchannels 43 in each microneedle 32. A structural support member 38  
interconnects microneedles 32. One or more input ports 37 and output ports 39 are  
located in microneedles 32. One or more active components 17 are located in each of  
microneedles 32.

5 Another active microneedle array 42b is shown in Figure 6B. The  
microneedle array 42b has a two-dimensional configuration with similar components  
as microneedle array 42a, except that microneedle array 42b is formed without a  
coupling channel member. Accordingly, microneedle array 42b includes a plurality  
of microneedles 32 each with single lumen microchannels 43. The microneedles 32  
10 each terminate at a needle tip 33 and a structural support member 38 interconnects  
microneedles 32. One or more input ports 37 and output ports 39 are located in  
microneedles 32, and one or more active components 17 are located in each of  
microneedles 32.

15 Figure 7A depicts an active microneedle array 45a having a two-dimensional  
configuration with similar components as microneedle array 42a discussed above,  
except that microneedle array 45a has a dual lumen microchannel configuration.  
Accordingly, each microneedle 32 in array 45a is constructed to have a pair of  
microchannels 46a and 46b. A needle coupling channel member 36 with a coupling  
microchannel 47 therein provides a fluidic interconnection between microchannels  
20 46a and 46b in each microneedle 32. One or more input ports 37 and output ports 39  
are located in microneedles 32, and one or more active components 17 can be located  
in each microchannel of microneedles 32.

25 Figure 7B depicts an active microneedle array 45b having a two-dimensional  
configuration with similar components as microneedle array 42b discussed above,  
except that microneedle array 45b has a dual lumen microchannel configuration.  
Accordingly, each microneedle 32 in array 45b is constructed to have a pair of  
microchannels 46a and 46b. A structural support member 38 interconnects  
microneedles 32, and one or more input ports 37 and output ports 39 are located in  
microneedles 32. One or more active components 17 can be located in each  
30 microchannel of microneedles 32.

In other alternative embodiments, active microneedle arrays can be fabricated  
to have additional microchannels in each microneedle. For example, each



1 microneedle in the array can have a tri-lumen channel construction such as shown for the microneedle of Figure 2B discussed above.

It should be understood that the above discussion related to microneedle arrays is equally applicable to macroneedles, which can be configured in various arrays. The  
5 macroneedle arrays can have similar structures as described above for the microneedle arrays such as single or multi-lumen channel configurations, multiple input and output ports, structural support members, coupling channel members, and active components in the macroneedles.

A method of fabricating a two-dimensional microneedle array according to the  
10 invention is depicted schematically in Figures 8A-8F. As shown in Figure 8A, a substrate 26 having a substantially planar surface 27 is provided, such as a silicon wafer which is polished on both sides. The wafer can have a thickness of about 1  $\mu\text{m}$  to about 700  $\mu\text{m}$ , and is preferably about 150  $\mu\text{m}$  thick. One side of the wafer is heavily doped with boron using high temperature thermal diffusion in order to form a  
15 3-5  $\mu\text{m}$  thick p+ layer. Next, silicon nitride ( $\text{Si}_3\text{N}_4$ ) is deposited on both sides of the wafer using plasma-enhanced chemical vapor deposition (PECVD). The silicon nitride on the undoped side of the wafer is patterned and etched employing photoresist as a mask, and then isotropic etching (a  $\text{CF}_4$  plasma for example) is used to etch the  
20 exposed silicon nitride to define the area upon which the microneedles are to be fabricated. After patterning the silicon nitride layer, the exposed silicon is anisotropically etched using a potassium hydroxide (KOH) solution. The p+ boron layer serves as an etch stop, resulting in a thin sacrificial membrane 52, as shown in Figure 8A. The sacrificial membrane 52 comprises the surface upon which the microneedles are formed and then subsequently released as described below.

25 Next, a metal system of adhesion layers and an electroplating seed layer are deposited (by electron beam evaporation, for example) onto the insulating silicon nitride film. The adhesion and seed layers are typically composed of, but not limited to, titanium, chromium, copper, or combinations thereof. Then, using a mask of the appropriate dimensions and standard photolithographic techniques, this metal  
30 multilayer is patterned. A metal material is then electroplated to form one or more bottom walls 54 (e.g., about 20  $\mu\text{m}$  thick) for the microneedles, as shown in Figure 8B. Palladium is one preferred metal for the bottom wall since it provides high

1 mechanical strength and durability, is corrosion resistant, provides biocompatibility  
for use in biomedical applications, and is easily electroplated to within precise  
dimensions. Other materials which fit the criteria mentioned could also be used  
equally well, such as copper, nickel, or gold. When performing the electroplating, the  
5 bath chemistry and the electroplating conditions (such as amount of applied current  
and time in the electroplating bath) should be precisely controlled for optimum  
results. The typical dimensions for bottom walls 54 are about 10-20  $\mu\text{m}$  in thickness,  
and about 50  $\mu\text{m}$  wide.

10 After bottom walls 54 have been formed, a commercially available thick  
photoresist is deposited (e.g., about 20  $\mu\text{m}$  thick) and patterned using ultraviolet  
exposure and alkaline developer, resulting in sacrificial layers 56 as depicted in  
Figure 8C. Next, a metal seed layer such as gold is sputter deposited (e.g., about 800  
 $\text{\AA}$  thick) onto the photoresist sacrificial layers 56. The metal seed layer serves as an  
15 electrical contact for the subsequent metal electroplating.

A metal layer such as palladium is then electroplated (e.g., about 20  $\mu\text{m}$  thick)  
onto sacrificial layers 56 to form a plurality of side walls 58 and top walls 60 of each  
microneedle, as shown in Figure 8D. The exposed metal seed layer is then removed  
using wet etching techniques to expose the underlying photoresist. Once the metal  
seed layer has been etched, the wafer is placed in an acetone bath to remove the  
20 photoresist from inside the microneedle structures, thereby producing a plurality of  
hollow microneedles 28, as shown in Figure 8E.

In the final processing step, sacrificial membrane 52 is removed by an  
isotropic etching technique, such as reactive ion etching in a  $\text{SF}_6$  plasma. Thus, the  
microneedle ends are released from sacrificial membrane 52 and are freely suspended,  
25 projecting outward from substrate 26, as depicted in Figure 8F and in the embodiment  
of Figure 3.

Alternatively, the fabricating method outlined above can be used to form a  
multilumen microneedle by forming bottom walls 54 with zero spacing therebetween  
on substrate 26 and carrying out the remaining steps as described above. A resulting  
30 multilumen microneedle 62 with a plurality of microchannels 64 therein is shown in  
Figure 8G.

In an alternative fabrication method, the microneedle array can be released

1 from substrate 26 following surface fabrication on substrate 26, such as for the  
embodiment shown in Figure 4. This method does not require sacrificial membrane  
formation or KOH etching. Instead, the needle arrays are released using wet etching  
of the seed metal from underneath the needle structures. If the seed metal is copper,  
5 for example, then this can be done by a selective etch of ammonium hydroxide  
saturated with cupric sulfate.

Arrays of two up to hundreds of microneedles can be easily and economically  
fabricated in a package with dimensions on the order of millimeters according to the  
above procedure. A single microneedle such as shown in Figure 1B can also be  
10 fabricated according to the procedure outlined above. In addition, instead of having  
the fluid outlet at the tips of the microneedles, fluid outlet ports can be etched into the  
side walls, top walls, and/or bottom walls of the microneedles if a larger amount of  
fluid transfer is desired.

Using the above fabrication methods provides the flexibility to integrate many  
15 additional functions directly onto the microneedles. These fabrication methods are  
low temperature and are compatible with integrated circuit (IC) technology as a post  
process. For example, various active components such as sensors, transducers, and  
electronic interfaces may be fabricated as integrated components on-chip during the  
needle fabrication process. An example of a procedure for fabricating a microneedle  
20 with on-chip devices such as CMOS (complementary metal-oxide semiconductor)  
devices is disclosed in U.S. Patent No. 5,591,139 to Lin et al., the disclosure of which  
is incorporated by reference herein. Alternatively, the active components may be in  
the form of prefabricated chips which are subsequently placed within the needle  
channels.

25 All of the needle devices including microneedles and arrays of the present  
invention can be coated on the inside with biocompatible materials, such as silicon  
nitride, gold, plastics, etc., by conventional coating processes known to those skilled  
in the art.

30 In addition, a light enhancing reflective coating can be formed on the inner  
surfaces of the active needle devices defining the lumens therein. The reflective  
coating can enhance the light output generated during a bioluminescent reaction in a  
bioluminescent-based active needle to provide for more sensitive biosensing

1 capabilities. Suitable reflective materials that can be used to coat the inner surfaces of  
the needle devices include silver, chromium, titanium, platinum, combinations  
thereof, and the like. Increased light intensity has also been observed for long narrow  
5 channels, which can be used to effectively design a bioluminescent-based micro-  
needle. Further details related to light enhancement of micro reaction chambers and  
long narrow (micro) channels are described in Bartholomeusz et al.,  
“BIOLUMINESCENT BASED BIOSENSOR FOR POINT-OF-CARE  
DIAGNOSTICS,” First Annual International IEEE Conference on Microtechnology,  
Medicine, and Biology, Lyon, France, October 12-14, 2000, the disclosure of which is  
10 incorporated by reference herein.

Figures 9A and 9B depict alternative methods of assembling two-dimensional  
needle arrays into three-dimensional needle array devices. In the method depicted in  
Figure 9A, a plurality of two-dimensional microneedle arrays 70 are provided which  
have been released from a substrate as shown for the array of Figure 4. The  
15 microneedle arrays 70 are positioned in a stacked configuration with a plurality of  
metallic spacers 72 therebetween to define the distance between any two microneedle  
arrays in the stack. The stacked needle array configuration is then subjected to flash  
electroplating to join microneedle arrays 70 with metallic spacers 72 in a fixed three-  
dimensional needle array device 74. The needle array device 74 can then be disposed  
20 in a machined interface structure 76, such as an acrylic interface, allowing connection  
to a dispensing means for injecting a liquid such as a syringe.

In the method depicted in Figure 9B, a plurality of two-dimensional  
microneedle arrays 80 are provided on substrates 82 such as shown for the  
microneedle array of Figure 3. The microneedle arrays 80 are positioned in a stacked  
25 configuration, with substrates 82 acting as spacers between arrays 80, to define the  
distance between any two microneedle arrays in the stack. The stacked array  
configuration is placed in a mold 84 such as an aluminum mold for plastic injection  
molding. The stacked array configuration is then subjected to plastic injection  
molding. This bonds microneedle arrays 80 together with a plastic molding material  
30 86, thereby forming a fixed three-dimensional needle array device 88. The array  
device 88 can then be disposed in an interface structure 76 allowing connection to a  
dispensing device such as a syringe.

1 In another alternative method of assembling two-dimensional needle arrays  
into three-dimensional needle array devices, the two dimensional arrays are manually  
assembled under a microscope. The two-dimensional arrays are stacked with spacers  
or with substrates on the arrays and are bonded together with a polymeric adhesive  
5 such as a UV-curable adhesive to form a three-dimensional needle array device,  
which can then be disposed in an interface structure.

The fabricated three-dimensional needle array devices are typically  
dimensioned to have a length of about 5 mm, a width of about 5 mm, and a height of  
about 2 mm.

10 The interface structures for connection to a syringe can be made from a variety  
of plastic materials such as acrylics, polystyrene, polyethylene, polypropylene, and  
the like. The interface structure typically accommodates a three-dimensional needle  
array device having up to about 25 two dimensional arrays. The interface structures  
are bonded to the three-dimensional needle array devices with a polymeric adhesive  
15 such as a UV-curable adhesive. The interface structures are configured to accept  
direct syringe connection via a connection means such as a conventional Luer-lock  
connector. Alternatively, interface structures can be formed for a single two-  
dimensional array or a single microneedle so as to accept direct syringe connection  
via a connector such as a Luer-lock connector.

20 In alternative embodiments of the invention, any of the above described array  
embodiments can be fabricated as a slanted active needle array, with needles in the  
array having varying lengths. The slanted needle array allows for collection of  
interstitial fluid samples at different depths during sample acquisition from a patient.  
Additionally, the slanted needle array allows for dispensing of medicaments into a  
25 patient at multiple depths throughout and beneath the dermal layers of the skin.

Further details regarding suitable microneedle and microneedle arrays suitable  
for use in the present invention are described in copending application Serial No.  
PCT/US99/21509, filed September 17, 1999, entitled "Surface Micromachined  
Microneedles" and which is incorporated by reference herein.

30 As discussed above, one or more active components such as a biosensor can  
be placed or integrated directly into the needle devices of the present invention. A  
biosensor is basically an analytical device that converts the concentration of an

1 analyte in a sample into an electrical signal by way of a biological sensing element  
intimately connected with a transducer. A particularly suitable biosensor useful in the  
needle devices of the invention is a bioluminescence-based biosensor, which can be  
employed in any of the above described embodiments. Such a biosensor can be  
5 formed by depositing biochemical sensing reagents on one or more inner walls of a  
needle device. For example, various bisensing reagents can be drawn into and dried  
down onto the inner walls of the hollow microneedle or microneedle arrays described  
previously. Bioluminescence-based biosensors are particularly suitable for  
monitoring metabolic levels, such as the level of creatine or glucose in blood.  
10 Generally, bioluminescent detection of the biosensor output is performed at the output  
ports of the microneedle.

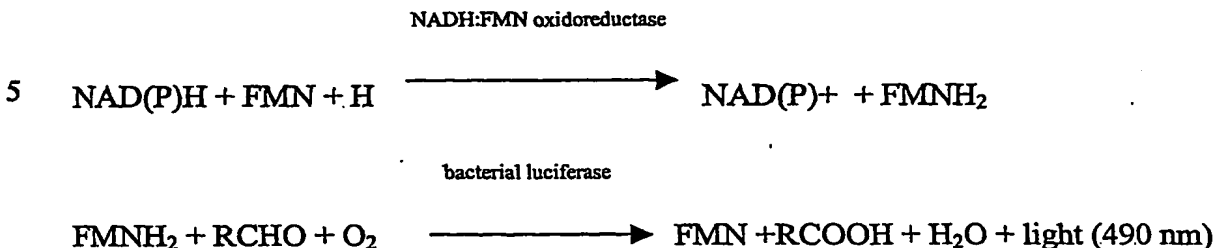
Bioluminescence-based chemical analysis has the advantages of being  
substantially more sensitive than conventional chromogenic (absorbance)  
measurements and is known to be accurate over a range of five or more orders of  
15 magnitude of concentration ranges. It is known that firefly bioluminescence occurs  
by enzyme-catalyzed oxidation of luciferin utilizing adenosine triphosphate (ATP).  
Bacteria bioluminescence is closely coupled to nicotinamide adenine dinucleotide  
hydride (NADH). Bioluminescent-based chemical analysis has the potential of  
measuring a wide range of metabolites from smaller sample volumes.

20 Since most metabolites in the body are within one or two reactions from ATP  
or NADH, they can be measured by coupling other enzyme reactions to an ATP or  
NADH bioluminescent reaction and measuring the light output. During the  
production or consumption of a metabolite of interest, enzyme linked reactions will  
cause the production or consumption of ATP (or NADH) through the following  
25 bioluminescent platform reactions.

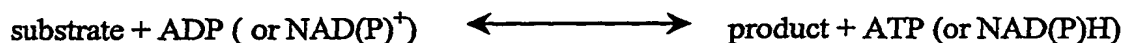
The ATP platform is based on the firefly luciferase reaction:



- 1 The NADH platform reaction based on NADH:FMN oxidoreductase and Bacterial Luciferase:



- 10 Substrates are coupled to these platform reactions through the following generic reaction:



- 15 The detected changes in light intensity (measured by various light detectors as described below) will be stoichiometrically proportional to the time changing concentration of the platform molecule (ATP or NADH) and thus proportional to the metabolite of interest. The bioluminescent platform reactions can be used to measure metabolites such as L-Phenylalanine, D-Glucose, L-Lactate, glucose 6-phosphate, glucose 1-phosphate, UDP-glucose, UDP-galactose, lactose, alkaline phosphatase, galactose in solution, human blood (serum & plasma), sweat, and human milk.

- 20 The light produced in the bioluminescent platform reactions can be detected by an optical detector such as a photodiode or charge coupled device (CCD). Such photosensing devices can be integrated inside a microneedle to detect the light, or can be located externally and can be used to detect the luminescence through a window in a microneedle surface. Depending on the instrument used to detect the luminescence, nanomolar, picomolar or even femtomolar analyses are possible. With increased sensitivity, smaller amounts of sample fluid are required for accurate analysis. A 0.05 micro-liter sample size that can be drawn by the microneedles can painlessly access small amounts of body fluid that can be analyzed via bioluminescence.

- 30 The transmittance of light through a medium across a certain length ( $l$ ) is specified through Beer's law,  $T = 10^{-\text{Absorbance}}$ , where  $\text{Absorbance} = \epsilon_\lambda C_B (l-x)$ , and  $\epsilon_\lambda$  is the molar absorption coefficient in  $\text{dm}^3/\text{mole-cm}$ , and  $C_B$  is the concentration in  $\text{mole/dm}^3$ . Assuming the light travels through a homogeneous medium along length

1 mole/dm<sup>3</sup>. Assuming the light travels through a homogeneous medium along length  
(*l*), the total transmitted light (*T*) can be expressed as:

$$T_{total(l)} = \int_{length} 10^{-\epsilon_{\lambda} C_B (l-x)} dx = (1-10^{-l}) / Ln10$$

5 where  $\epsilon_{\lambda} C_B$  is assumed to be 1 for simplicity. For a pyramid (which is the shape of  
the etched wells of the <100> silicon wafers), where the peak depth of the pyramid is  
equal to the length (*l*) and the base width of the pyramid is (*a*), the transmittance is  
integrated through the viewing area and is equal to  $T_{total(l)} \cdot a^2/3$ . Thus, a linear  
correlation of a volume versus integrated luminosity plot for a given viewing window  
10 should indicate a transmittance proportional to signal intensity (average CCD counts  
over the viewing area, for example). A flat bottom well with a reflective surface will  
have a transmittance of  $T_{total(2l)}$ , and will be about twice as large as  $T_{total(l)}$  (when length  
<< 1<sup>cm</sup>). Thus, the slope of a linear fit of volume versus integrated luminescence  
intensity for a reflective surface of a given viewing window should be about twice  
15 that of a non-reflective surface due to the increased transmittance.

The enzymes suitable for use in the bioluminescent platform reactions of the  
biosensors are inherently robust and stable, retaining their activity after lyophilization,  
deposition, and rehydration. The reagent/enzyme mixture or "cocktail" used to detect  
various metabolites is drawn into the needles after fabrication, lyophilized (freeze  
20 dried) in a stable state, and then packaged for long term storage (up to a year  
depending on the analytes, reagents, and enzymes needed). The reagent/enzyme  
mixture includes the ATP and NADH bioluminescent platform enzymes and the  
enzymes that couple the metabolites to the platforms, as well as all the necessary  
reagents needed to complete all the reactions that lead to the light output.

25 The methods used for preparing and storing reagent/enzyme mixtures inside  
the bioluminescent-based active needle devices are discussed as follows.

#### 1. Drawing of Reagent/Enzyme Mixtures into the Needle Lumen(s)

The reagent/enzyme mixtures or "cocktails" are prepared as a "wet" solution  
in the concentrations needed to detect the desired analytes from the sample volume  
drawn through the needle lumen. Anti-oxidants and other enzyme stabilizing agents  
30 are added to the "cocktail" before lyophilization. These enzyme-stabilizing agents are  
described below in the lyophilization process.



1       The prepared wet solutions are drawn into the needles by capillary action.  
The filling of the needles is ensured by oxidizing the lumen of the needle during the  
needle fabrication process (or at least using a hydrophilic metal for the lumen of the  
needle). Each needle lumen has a different "cocktail" for measuring different  
5       analytes. Reagents and enzyme-stabilizing agents can be added to an agarose solution  
which is dried during the lyophilization process and allows for the sample fluid to be  
drawn into the needle faster by capillary action.

## 2.       Lyophilization Process

10       Lyophilization stabilizes enzymes for long-term storage by reducing both  
mechanical and chemical degradation. Appropriate stabilizing excipients and  
preservatives minimize the denaturation often observed during the processes of  
lyophilization. Optimized process variables include the initial concentration of  
enzyme, buffers that exhibit minimal changes in pH with freezing and drying,  
freezing rate (should be slow), and various additives.

15       The glass transition temperature of the amorphous phase of the lyophilized  
enzyme needs to exceed the planned storage temperature of the needle devices. Glass  
transition temperature of the lyophilized enzyme can be increased by using  
disaccharides and polymers (used in combination with disaccharides). Disaccharides  
such as sucrose and trehalose are especially good at stabilizing the enzyme during  
20       freezing and dehydration. The sugar to protein weight ratio should be at least about 1  
to 1, although stability can be further increased with greater sugar (5 to 1 ratio).  
Reducing sugars such as glucose, lactose, maltose or maltodextrins should be avoided  
because of their tendency to degrade proteins through the Maillard reaction between  
the carbonyls of the sugar and the free amino groups of the protein. Furthermore,  
25       surfactants can be used to inhibit aggregation at very low concentrations, such as less  
than about 0.5% per volume.

30       Antioxidants such as dithiothreitol and glutathione are used during  
lyophilization and subsequent storage to prevent oxidation of firefly luciferase due to  
sulfhydryl groups. Bovine serum albumin can be used for surface passivation.  
Polyethylene oxide (PEO)-based polymers and surfactants are also effective for  
surface passivation. Various enzyme preservation and stabilization cocktails are well  
known and widely used to maintain enzyme activity under dry storage conditions. In

1 one embodiment of the invention, bioluminescent reagents are preserved and  
stabilized with the following components: (1) 0.45 M glycyl glycine buffer (pH 7.8);  
(2) 1 mM EDTA; (3) 1mM dithiothreitol; (4) 10 mM MgSO<sub>4</sub>; (5) 1 mg/ml of bovine  
serum albumin; (6) 1 wt% sucrose; and (7) 1 wt% Dextran T-40. It has been found  
5 that such a mixture is suitable for stabilization of creatine kinase, a particularly  
delicate enzyme.

The actual bioluminescent molecules (ATP, FMN, bacterial and firefly  
luciferase, Oxidoreductase, etc.) are added to the preservative reagents, mixed  
thoroughly and added to each channel of a pre-chilled biosensor. In one preferred  
10 method, the biosensor and reagents are rapidly frozen to about -70°C followed by a  
two-stage lyophilization process. The first stage of lyophilization proceeds for 24  
hours at about -50°C and less than about 100 mTorr of pressure. The second stage of  
lyophilization proceeds for an additional 24 hours at about +30°C and less than about  
100 mTorr of pressure. Air is then re-admitted to the lyophilization chamber and the  
15 biosensors are removed. Each completed biosensor is then stored in a black plastic  
container with a gas tight lid that also contains a desiccant and a humidity indicator  
membrane. It has been found that this method used with firefly luciferase can  
preserve more than half the enzymatic bioluminescent activity for a minimum of six  
months.

20 The interaction between histidine and Ni<sup>++</sup> can also be used for immobilization  
of the enzyme. In biosensor applications, enzymes can be immobilized on a solid  
support to prevent diffusion (into the sample solution) and minimize interference with  
other channels of the sensor. The performance of the sensor can be adjusted by  
changing the immobilized enzyme amount. The recombinant enzymes with BCCP  
25 domains can be immobilized through this interaction with high affinity ( $K_a=10^{15} \text{ M}^{-1}$ ).  
There are a variety of solid matrices that can be used for immobilization.

Co-immobilization of sequentially operating enzymes improves total reaction  
efficiency, leading to higher sensitivity. A coupled assay with coimmobilized  
30 luciferase and flavin reductase has the advantage that the FMNH<sub>2</sub> produced from the  
flavin reductase can be used more effectively for the luciferase reaction, reducing its  
autooxidation. Traditional immobilization methods use chemically conjugated  
enzymes on solid materials, resulting in low immobilization efficiency and low and

1 inconsistent enzyme activity, due to nonspecific immobilization and surface-induced activity loss.

2 In one method of the invention, a biotin-avidin system for protein  
3 immobilization is utilized, due to its high affinity ( $K_a=10^{15}/M$ ) and stability. In  
4 another method, *V. harveyi* luciferase and FRase I biotinylated is produced in vivo,  
5 the proteins are immobilized on avidin-conjugated beads, and the enzyme beads are  
6 used to assay NADH. In using this method, it has been found that the co-immobilized  
7 enzymes had eight times higher bioluminescence activity than the free enzymes at low  
8 enzyme concentration and high NADH concentration. In addition, the immobilized  
9 enzymes were more stable than the free enzymes. This immobilization method is also  
10 useful to control enzyme orientation, which can increase the efficiency of sequentially  
11 operating enzymes like the oxidoreductase-luciferase system.

### 3. Storage of Active Needle Devices

12 Storing the bioluminescent-based active needle sensors with the lyophilized  
13 "cocktail" in a desiccant will ensure that glass transition temperatures of the  
14 lyophilized enzyme are greater than storage temperatures. The active needle devices  
15 should be stored in the dark to minimize photooxidation.

16 Further details regarding bioluminescence-based biosensors as used in the  
17 present invention are set forth in the Examples section below.

18 Another sensor that can be utilized in the needle device of the invention is an  
19 integrated pressure sensor in the form of an optical Fabry-Perot cavity, which is  
20 depicted in Figure 10. The pressure sensor can be integrated into any of the above  
21 embodiments by forming a glass plate 120 on one interior surface 121 of a hollow  
22 microneedle. A cavity 125 is etched in glass plate 120 on the side of the sensor which  
23 is to be in proximity to the fluid flowing in the microchannel of the needle. A thin  
24 silicon diaphragm 126 (*e.g.*, about 25 microns thick) is affixed over cavity 125 and is  
25 configured to be in direct contact with a fluid whose pressure is to be measured. The  
26 diaphragm 126 deflects in response to applied pressure. A light beam 129 (*e.g.*,  
27 produced by an LED) is coupled into the sensor through optical fiber 128. The optical  
28 fiber 128 optically communicates with the interior of the microneedle through a  
29 window 124 in the side of the microneedle. Pressure changes from fluid flowing past  
30 diaphragm 126 cause the diaphragm to move. The cavity 125 functions as a Fabry-

1 Perot cavity and the diaphragm reflects varying amounts of light intensity which is  
directly proportional to the amount of pressure applied to the diaphragm by the fluid.  
The reflected light can be coupled as a signal out 130 through optical fiber 128 to an  
appropriate analyzing device for measurement. The change in reflected light can be  
5 measured and with proper calibration, can provide a linear measurement of the  
amount of pressure in the fluid.

The active needle devices of the invention such as the microneedle and  
microneedle arrays have many benefits and advantages. For fluid injection, these  
benefits include reduced trauma at penetration sites due to their small size, greater  
10 freedom of patient movement because of the minimal penetration depth of the  
needles, a practically pain-free drug delivery due to the smaller cross section of the  
needle tip and distribution of fluid force, and precise control of penetration depth from  
needle extension length. In addition, the microneedles have the ability to deliver  
drugs to localized areas, or extract fluids from precise locations for analysis, and are  
15 advantageous in their ability to be stacked and packaged into a three-dimensional  
device for fluid transfer. The active microneedles have the ability to extract either  
large or small amounts of fluids in precisely controlled amounts, and can be easily  
and economically fabricated using micromachining procedures.

The active microneedles also provide convenient and easy methods for  
20 performing electrical, optical, physical, or biochemical sensing in compact devices.  
The integrated sensing capabilities in the active microneedles provide compact,  
portable, and disposable devices which are less costly and complex to use for analysis  
of fluid samples, and reduce or eliminate the need for supporting fluidic and  
electronic systems.

25 The microneedles can be used in a wide variety of biomedical applications.  
The microneedles can withstand typical handling and can subcutaneously deliver  
medication without the usual discomfort associated with conventional needles. The  
microneedles are minimally invasive, in that the microneedles only penetrate just  
beyond the viable epidermis, reaching the capillaries and minimizing the chance of  
30 encountering and damaging the nerves present in the area of penetration.

The following examples are given to illustrate the present invention, and are  
not intended to limit the scope of the invention.

1

Example 1

5

10

A two dimensional microneedle array was fabricated with 25 hollow microneedles fluidly interconnected by a needle coupling channel. The hollow microneedles were made such that their inner cross-sectional area was  $40 \times 20 \mu\text{m}^2$  (width by height) and their outer cross-sectional area was  $80 \times 60 \mu\text{m}^2$ . The needle coupling channel was  $100 \mu\text{m}$  wide, and provided fluid communication between each needle channel. Two sets of  $60 \times 100 \mu\text{m}^2$  structural supports were located  $250 \mu\text{m}$  from each needle end. Each needle channel was 2 mm long, while the width of the 25 needle array was 5.2 mm. The center-to-center spacing between individual needles was  $200 \mu\text{m}$ . The needle walls were made of electroformed metal and were approximately  $20 \mu\text{m}$  thick.

15

The microneedle array was fabricated from electroformed low stress nickel sulphamate, gold cyanide, and palladium electroforming solutions. The bath chemistry and electroplating conditions were selected and precisely controlled to allow formation of low stress depositions on top of a  $3\text{-}5 \mu\text{m}$  sacrificial membrane. The surface roughness of the electroplated metals was found by Atomic Force Microscope (AFM) to be approximately 15 nm, resulting in a relative roughness of 0.00056.

20

It is important to note the structural quality of the needle tips. The inner dimensions were approximately  $30 \times 20 \mu\text{m}^2$ , outer dimensions were approximately  $80 \times 60 \mu\text{m}^2$ , and the needle tips were formed with  $45^\circ$  angles for ease of penetration.

25

Example 2

30

Individual hollow metallic microneedles were fabricated with multiple output ports and had an inner cross-sectional area of  $140 \times 21 \mu\text{m}^2$  (width by height) with outer cross-sectional area dimensions of  $200 \times 60 \mu\text{m}^2$ . The tip dimensions of the microneedles were less than  $15 \times 15 \mu\text{m}^2$ . The length of the tapered portion of the needle shaft was 1 mm and the distance from the tip to the first output port was about  $300 \mu\text{m}$ . The total length of each microneedle was 6 mm, with input port inner dimensions of  $140 \mu\text{m}$  wide and  $21 \mu\text{m}$  high. The wall thickness of each microneedle

1 was about 20  $\mu\text{m}$ , and the output ports were formed with dimensions of 30  $\mu\text{m}^2$  on the top and bottom of the microneedles. The output ports were separated by 30  $\mu\text{m}$ , and there were 9 ports on the top and 12 ports on the bottom of each microneedle.

5 The microneedles were each packaged into a standard Luer-lock fitting using a polymeric medical grade UV-curable adhesive. This interface between a microneedle and a syringe included a simple female luer-to-1/16" barb adapter. The UV-curable adhesive was found to permanently affix the microneedle to the interface while providing a leak resistant seal.

### 10 Example 3

A preliminary experiment was conducted to assay a glucose via glucokinase and firefly luciferase reactions. The assay was a homogeneous ATP depletion type assay with initial concentrations of glucokinase (80 nano-molar), ATP (10 micro-molar), luciferein (100 micro-molar), and firefly luciferase (0.1 nano-molar) in 0.45 M glycyl glycine buffer at pH 7.8. The results are shown in the graph of Figure 11, which plots the normalized luminometer bioluminescence, detected two minutes after the rapid mixing of all reactants, as a function of initial glucose concentration. The results suggest that a single step homogeneous assay for glucose can be accomplished without initial dilution of the glucose in the sample.

### 20 Example 4

Figures 12 and 13 are graphs showing the characteristics for a creatine biosensor. The graph of Figure 12 plots the normalized bioluminescent signal (in relative light units) as a function of time for several different concentrations of creatine. The bioluminescent signal had a 560 nm wavelength and was measured by a luminometer. The final concentrations of creatine shown are within the physiological serum creatine concentration range.

30 Figure 13 shows the results of an assay experiment for creatine using the creatine kinase and firefly luciferase reactions. The creatine assay was a homogeneous ATP depletion assay (the creatine kinase reaction competes with the firefly luciferase reaction for the ATP). The final assay constituents were buffered in 0.45 molar glycine-glycine buffer at pH 7.8 and the final assay concentrations were

1 the following: 1.4  $\mu\text{M}$  ATP , 71  $\mu\text{M}$   $\text{Mg}^{2+}$ , 14  $\mu\text{M}$  luciferin, 0.3  $\mu\text{M}$  luciferase, 60  
2  $\mu\text{M}$  creatine kinase, and various concentrations of creatine (0.45 M glycine-glycine  
3 buffer for control). Relative light units (RLU) measured by the luminometer are  
4 dependent on the type of instrument, sensitivity of the instrument, and other factors;  
5 therefore, the raw bioluminescence signal measured versus time was normalized to  
6 the control peak RLU value. Figure 13 plots the normalized bioluminescent signal as  
7 a function of creatine concentration.

#### Example 5

10 In order to determine the feasibility and the physical limitations of using  
11 bioluminescence for highly sensitive analyte measurement of small sample volumes,  
12 micro- reaction chambers ( $\mu\text{RCs}$ ) were fabricated on silicon wafers using KOH  
13 anisotropic wet etching. An ATP firefly luciferase/luciferin solution was placed in  
14 the  $\mu\text{RCs}$  and observed through a close up lens with a CCD. The integrated CCD  
15 signal was recorded and compared with well size and depth. The attenuation of the  
16 CCD signal was also observed for wafers coated with titanium (500Å) followed by  
17 chromium (1500 Å).

18 A 5-mL firefly luciferase/luciferin solution consisted of 1.25 mg/mL bovine  
19 serum albumin (Sigma - reconstituted into the solution and used for coating the glass  
20 vial to prevent denaturing of the luciferase), 1.25 mM ethylene diaminetetra acetic  
21 acid (Sigma), 12.5 mM  $\text{Mg}^{++}$  (Sigma - from  $\text{MgSO}_4$ ), 1.84- $\mu\text{M}$  firefly luciferase  
22 (Promega), and 1.25 mM luciferin (Biosynth) in a 1.25 mM glycyl-glycine buffer.  
23 This mixture was able to maintain 90% activity for about 20 hours when stored in the  
24 dark. A 5 mM ATP, glycyl-glycine buffer solution was also prepared. A 20  $\mu\text{L}$   
25 sample of the firefly luciferase/luciferin solution was pipetted into 5  $\mu\text{L}$  of the ATP  
26 solution that resulted in a 1.0 mM ATP mixture, saturated with luciferase and  
27 luciferin (which means the reaction rate was at its peak). After the solution mixed, 20  
28  $\mu\text{L}$  of it was pipetted onto an area about 20 x 15 mm wide. A thin glass cover slip  
29 was placed on the solution, starting at one end and tilting the cover slip as it was laid  
30 down, so that the excess bioluminescent fluid would disperse. For high  
31 concentrations of ATP ( $> 8 \mu\text{M}$ ), the initial mixing of ATP with the  
32 luciferase/luciferin solution causes a peak luminescence within 3 seconds. The

1 luminescence then tapers and levels off after 1 minute. Therefore, the light  
measurements for this experiment were integrated for 20 seconds, 2 minutes after the  
ATP and luciferase/luciferin solution were mixed, with the light intensity essentially  
constant.

5 An ST6-A CCD camera, from Santa Barbara Instruments Group was fitted  
with an Olympus wide-angle lens and close-up ring. The experimental substrates  
were focused 55 mm below the lens with the aperture set at 2.8. The field of view  
was about 20 x 15 mm. The camera was operated at -20.00 °C. One minute after the  
luciferase/luciferin solution was added to the ATP, a 10-sec dark field exposure was  
10 taken with the CCD. At 2 minutes and 5 seconds after the ATP and  
luciferase/luciferin solution mixed, the CCD integrated a 20 second exposure of the  
bioluminescent reaction while shrouded in a darkroom. The resulting image was  
saved as a TIF file (Range: 0-400). Scion Image (based on the NIH image software)  
was used to determine the average and standard deviation of the pixel values for each  
15  $\mu$ RC. One pixel of the CCD image was equal to 46.875  $\mu$ m. Actual results failed to  
show light emitting from the 75, 50, 25, and 10  $\mu$ m wide wells on all substrates.

Figure 14 is a graph of the average CCD counts from the 20 second integrated  
CCD reading as a function of different sample volumes. The data was plotted in sets  
20 for the same viewing area (or  $\mu$ RC square width). The data was also separated  
according to Ti/Cr reflective substrates and plain, non-reflective substrates. For each  
set of data (wells with same width and coating), the increasing volume occurs from  
the increased etch depths of 250  $\mu$ m, 100 $\mu$ m, and 50  $\mu$ m. The data from the different  
etch depths are pointed out for the 750  $\mu$ m wide wells as an example. The higher  
25 intensity values occurred for the deeper wells. The intensity/volumes slope is greater  
for the Ti/Cr reflective substrates than for the plain substrates.

Table 1 below sets forth a statistical comparison of the intensity/volume slope  
relationships for reflective vs. non-reflective surfaces of the same viewing window  
size. The reflective wells with intensity/volume slopes that were statistically different  
30 from the intensity/volume slopes for the non-reflective surfaces ( $P < 0.05$  using the T-  
test) were over two times greater. This follows the hypothesis that transmittance is  
nearly doubled for chromium coated (reflectivity = 0.67 @ 560 nm) versus uncoated  
silicon (reflectivity = 0.33 @ 560 nm)  $\mu$ RCs.



The T-test used was the student-T test to find if there was a significant difference between sample measurements of two groups. The null hypothesis of the T-test (for the described experiment of this example) was: there is no difference in the intensity/volume slopes for the wells with reflective surfaces and the wells with non-reflective surfaces. The value  $P < 0.05$  means that there is less than a 5% probability (P) that the null hypothesis is true. The T-test, if performed properly, is a useful tool to show that one method or product is significantly different (more efficient, better, etc.) than an existing method or product.

Table 1

$\mu$ RC Width ( $\mu$ m)	P value from T-test between Intensity/Volume Slopes of Non-Reflective $\mu$ RCs and Reflective $\mu$ RCs	Ratio of Intensity/Volume Slopes for Reflective and Non-Reflective Substrates
750	0.00001	3.02
500	0.002	2.37
400	0.004	4.94
300	0.005	5.11
250	0.36	2.87
200	0.030	1.07
150	0.72	0.88
100	0.55	0.21

The intensity/volume slope also increases as the  $\mu$ RC square width decreases. This implies that using long, narrow microneedles as the  $\mu$ RC is ideal. Table 2 statistically compares the intensity/volume slopes between reflective wells of different viewing window sizes, showing that there is a significant increase in the intensity/volumes slopes, as the  $\mu$ RC width decreases. The intensity/volume slope ratio is the slope for the smaller window over the slope for the next larger window.

1

Table 2

5	$\mu$ RC Square Widths Being Compared ( $\mu$ m)	P value from T-test between Intensity/Volume Slopes $\mu$ RCs being compared	Ratio of Intensity/Volume Slopes for Smaller $\mu$ RC Widths Verses Wider $\mu$ RC Widths
	500/750	0.004	1.89
	400/500	0.04	1.98
	300/400	0.28	1.59
	250/300	0.89	1.11
	200/250	0.81	1.28
	150/200	0.91	0.73

10

The increase in intensity/volume is only significant down to wells that are 400  $\mu$ m wide. For smaller  $\mu$ RC widths (150-300  $\mu$ m), the non-reflective substrates show little correlation between average CCD counts and sample volumes ( $R^2 < 0.25$ , where R is the reflectivity). The Ti/Cr reflective substrates still show some correlation ( $R^2 > 0.25$  for  $\mu$ RCs 250  $\mu$ m wide and wider) between intensity and volume. However, as the  $\mu$ RC square width decreases (250  $\mu$ m wide and smaller), there is little difference in signal intensity values for different etch depths. The error in the signals for wells 200  $\mu$ m wide and smaller is large enough to overlap with the background intensity. This suggests that the wells with windows smaller than 200  $\mu$ m wide would not produce signals of a discernable intensity, if they are only 250  $\mu$ m deep. However, narrower and deeper  $\mu$ RCs such as microneedles, which hold a larger sample volume, would produce a stronger useable signal.

15

20

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

25

What is claimed is:

30

- 1           1.     An active needle device, comprising:  
              a hollow non-silicon elongated shaft defining at least one channel and  
              having a proximal end and a distal end;  
              at least one input port at the proximal end of the elongated shaft and at  
5           least one output port at the distal end, the channel providing communication  
              between the at least one input port and the at least one output port; and  
              at least one active component in the device.
2.     The needle device of claim 1, wherein the elongated shaft is configured  
              to form a macroneedle.
- 10          3.     The needle device of claim 1, wherein the elongated shaft is configured  
              to form a microneedle.
4.     The needle device of claim 1, wherein the active component comprises  
              one or more components selected from the group consisting of electronic components,  
              electromechanical components, mechanical components, biochemical components,  
15           and combinations thereof.
5.     The needle device of claim 1, wherein the active component is selected  
              from the group consisting of a sensor, an actuator, and combinations thereof.
6.     The needle device of claim 5, wherein the sensor comprises a  
              biosensor.
- 20          7.     The needle device of claim 6, wherein the biosensor is a  
              bioluminescence-based biosensor.
8.     The needle device of claim 5, wherein the actuator comprises a  
              micropump or microvalve.
9.     The needle device of claim 1, wherein the active component comprises  
25           an integrated circuit chip.
10.    The needle device of claim 1, wherein the active component comprises  
              an optical detector.
11.    The needle device of claim 1, wherein the active component comprises  
              a transducer component.
- 30          12.    The needle device of claim 1, wherein the active component facilitates  
              taking one or more measurements selected from the group consisting of biochemical  
              measurements, optical measurements, electrical measurements, physical

1 measurements, and combinations thereof.

13. An active microneedle device, comprising:

a hollow non-silicon elongated shaft defining at least one microchannel and having a proximal end and a distal end;

5 at least one input port at the proximal end of the elongated shaft and at least one output port at the distal end, the microchannel providing communication between the at least one input port and the at least one output port; and

at least one active component located in the elongated shaft.

10 14. The microneedle device of claim 13, wherein the elongated shaft has a plurality of input ports.

15 15. The microneedle device of claim 13, wherein the elongated shaft has a plurality of output ports.

16 16. The microneedle array device of claim 13, wherein the elongated shaft is supported on a substrate.

17. The microneedle device of claim 13, wherein the active component comprises one or more components selected from the group consisting of electronic components, electromechanical components, mechanical components, biochemical components, and combinations thereof.

20 18. The microneedle device of claim 13, wherein the active component comprises a biosensor.

19. The microneedle device of claim 18, wherein the biosensor is a bioluminescence-based biosensor.

25 20. The microneedle device of claim 13, wherein the active component comprises a transducer component.

21. The microneedle device of claim 13, wherein the elongated shaft has at least one additional microchannel therein.

22. An active microneedle array device, comprising:

a substrate having a substantially planar surface;

30 a plurality of hollow non-silicon microneedles on the planar surface of the substrate, each of the microneedles having at least one microchannel that provides communication between at least one input

1 port at a proximal end of each of the microneedles and at least one  
output port at an opposite distal end that extends beyond an edge of the  
substrate; and

5 at least one active component located in one or more of the  
microneedles.

23. The microneedle array device of claim 22, wherein the microneedles  
comprise a two dimensional array.

24. The microneedle array device of claim 22, wherein the microneedles  
comprise a three dimensional array.

10 25. The microneedle array device of claim 22, wherein the microchannel  
in each of the microneedles has a cross-sectional area in the range from about  $25 \mu\text{m}^2$   
to about  $5000 \mu\text{m}^2$ .

15 26. The microneedle array device of claim 22, wherein the microneedles  
are composed of a metal material selected from the group consisting of nickel, copper,  
gold, silver, platinum, palladium, titanium, chromium, and alloys or combinations  
thereof.

20 27. The microneedle array device of claim 22, further comprising a  
coupling channel member that provides fluid communication between the  
microneedles.

28. The microneedle array device of claim 22, further comprising a pair of  
structural support members that mechanically interconnect the microneedles and that  
precisely control penetration depth of the microneedles

25 29. The microneedle array device of claim 22, wherein the microneedles  
have a plurality of input ports.

30. The microneedle array device of claim 22, wherein the microneedles  
have a plurality of output ports.

31. The microneedle array device of claim 22, wherein the active  
component comprises one or more components selected from the group consisting of  
30 electronic components, electromechanical components, mechanical components,  
biochemical components, and combinations thereof.

32. The microneedle array device of claim 22, wherein the active  
component comprises a biosensor.

- 1           33.    The microneedle array device of claim 32, wherein the biosensor is a bioluminescence-based biosensor.
34.    The microneedle array device of claim 22, wherein the active component comprises a transducer component.
- 5           35.    The microneedle array device of claim 22, wherein each of the microneedles have at least one additional microchannel therein.
36.    An active microneedle array device, comprising:  
                a plurality of hollow non-silicon microneedles each having at least one microchannel that provides communication between at least  
10               one input port at a proximal end of each of the microneedles and at least one output port at an opposite distal end;  
                at least one structural support member that interconnects the microneedles; and  
                at least one active component located in one or more of the  
15               microneedles.
37.    The microneedle array device of claim 36, wherein the microneedles comprise a two dimensional array.
38.    The microneedle array device of claim 36, wherein the microneedles comprise a three dimensional array.
- 20           39.    The microneedle array device of claim 36, further comprising a coupling channel member that provides fluid communication between the microneedles.
40.    The microneedle array device of claim 36, wherein the microneedles have a plurality of input ports.
- 25           41.    The microneedle array device of claim 36, wherein the microneedles have a plurality of output ports.
42.    The microneedle array device of claim 36, wherein the active component comprises one or more components selected from the group consisting of electronic components, electromechanical components, mechanical components,  
30               biochemical components, and combinations thereof.
43.    The microneedle array device of claim 36, wherein the active component comprises a biosensor.

1           44. The microneedle array device of claim 43, wherein the biosensor is a bioluminescence-based biosensor.

          45. The microneedle array device of claim 36, wherein the active component comprises a transducer component.

5           46. The microneedle array device of claim 36, wherein each of the microneedles has at least one additional microchannel therein.

          47. An active needle array device, comprising:

                  a plurality of hollow non-silicon needles each having at least one channel that provides communication between at least one input port at a proximal end of each of the needles and at least one output port at an opposite distal end; and

                  at least one active component located in one or more of the needles.

10           48. The needle array device of claim 47, further comprising a coupling channel member that provides fluid communication between the needles.

15           49. The needle array device of claim 47, wherein the needles have a plurality of input ports.

          50. The needle array device of claim 47, wherein the needles have a plurality of output ports.

20           51. The needle array device of claim 47, wherein the active component comprises one or more components selected from the group consisting of electronic components, electromechanical components, mechanical components, biochemical components, and combinations thereof.

25           52. The needle array device of claim 47, wherein the active component comprises a biosensor.

          53. The needle array device of claim 52, wherein the biosensor is a bioluminescence-based biosensor.

          54. The needle array device of claim 47, wherein the active component comprises a transducer component.

30           55. The needle array device of claim 47, wherein each of the needles has at least one additional channel therein.

          56. The needle array device of claim 47, wherein each of the needles is a

1 macroneedle.

57. The needle array device of claim 47, wherein each of the needles is a microneedle.

5 58. An active needle device, comprising:  
a hollow silicon elongated shaft defining at least one channel and having a proximal end and a distal end;

at least one input port at the proximal end of the elongated shaft and at least one output port at the distal end, the channel providing communication between the at least one input port and the at least one output port; and

10 at least one active component in the device, the active component comprising a bioluminescence-based biosensor.

59. An active microneedle device, comprising:

a hollow silicon elongated shaft defining at least one microchannel and having a proximal end and a distal end;

15 at least one input port at the proximal end of the elongated shaft and at least one output port at the distal end, the microchannel providing communication between the at least one input port and the at least one output port; and

20 at least one active component located in the elongated shaft, the active component comprising a bioluminescence-based biosensor.

60. An active microneedle array device, comprising:

a substrate having a substantially planar surface;

25 a plurality of hollow silicon microneedles on the planar surface of the substrate, each of the microneedles having at least one microchannel that provides communication between at least one input port at a proximal end of each of the microneedles and at least one output port at an opposite distal end that extends beyond an edge of the substrate; and

30 at least one active component located in one or more of the microneedles, the active component comprising a bioluminescence-based biosensor.



- 1           61.    An active microneedle array device, comprising:  
              a plurality of hollow silicon microneedles each having at least  
              one microchannel that provides communication between at least one  
5           input port at a proximal end of each of the microneedles and at least  
              one output port at an opposite distal end;  
              at least one structural support member that interconnects the  
              microneedles; and  
              at least one active component located in one or more of the  
              microneedles, the active component comprising a bioluminescence-  
10           based biosensor.
62.    An active needle array device, comprising:  
              a plurality of hollow silicon needles each having at least one  
              channel that provides communication between at least one input port at  
15           a proximal end of each of the needles and at least one output port at an  
              opposite distal end; and  
              at least one active component located in one or more of the  
              needles, the active component comprising a bioluminescence-based  
              biosensor.
63.    The needle device of claim 1, further comprising a reflective surface in  
20           the channel.
64.    The needle device of claim 58, further comprising a reflective surface  
              in the channel.
65.    The needle device of claim 47, wherein the needles have varying  
              lengths.
- 25           66.    The needle device of claim 62, wherein the needles have varying  
              lengths.

1 / 10

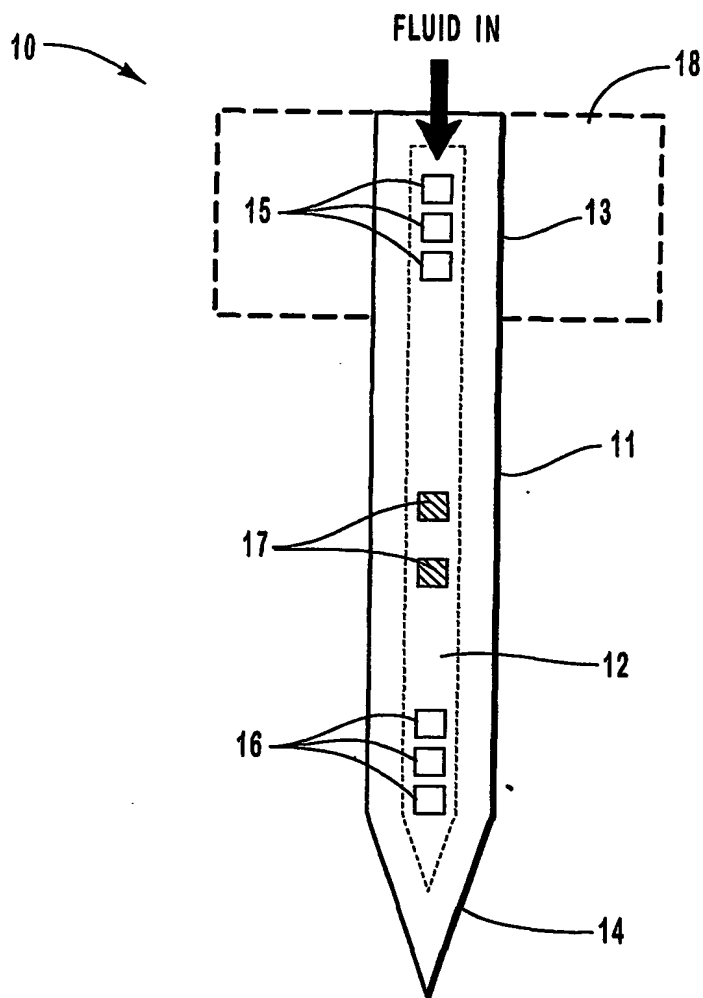


FIG. 1A

2 / 10

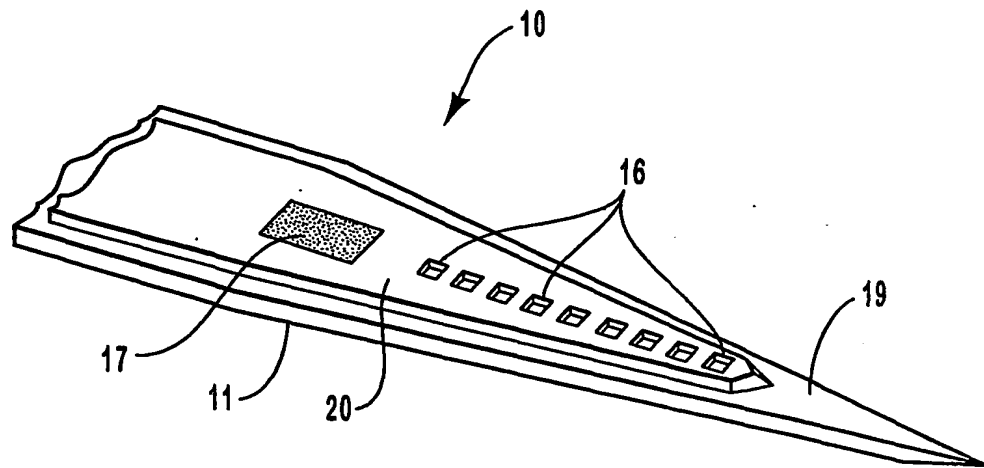


FIG. 1B

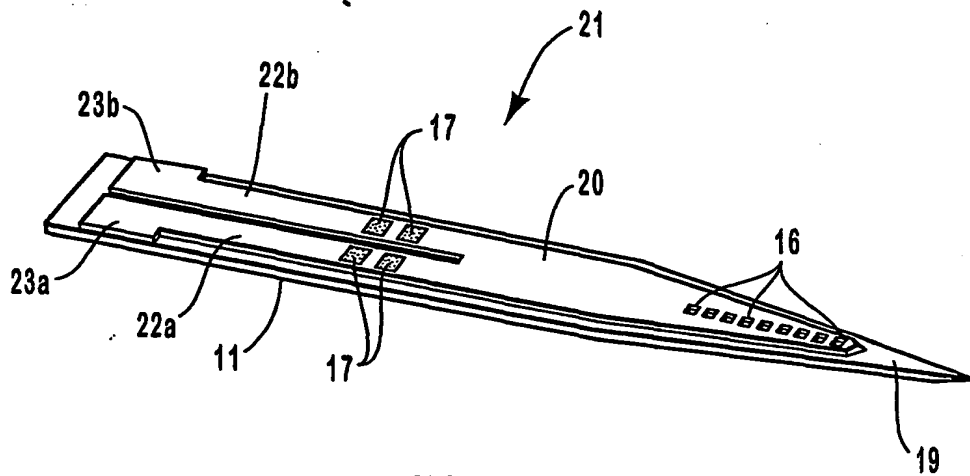


FIG. 2A

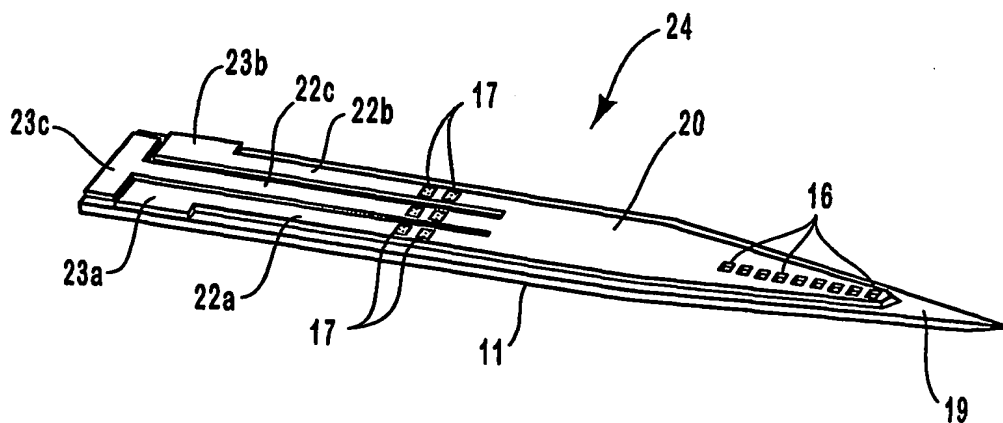


FIG. 2B

3 / 10

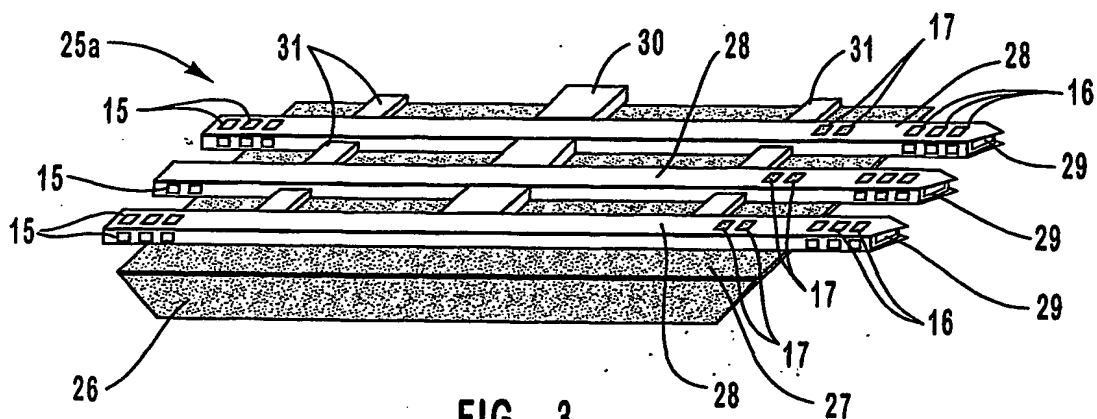


FIG. 3

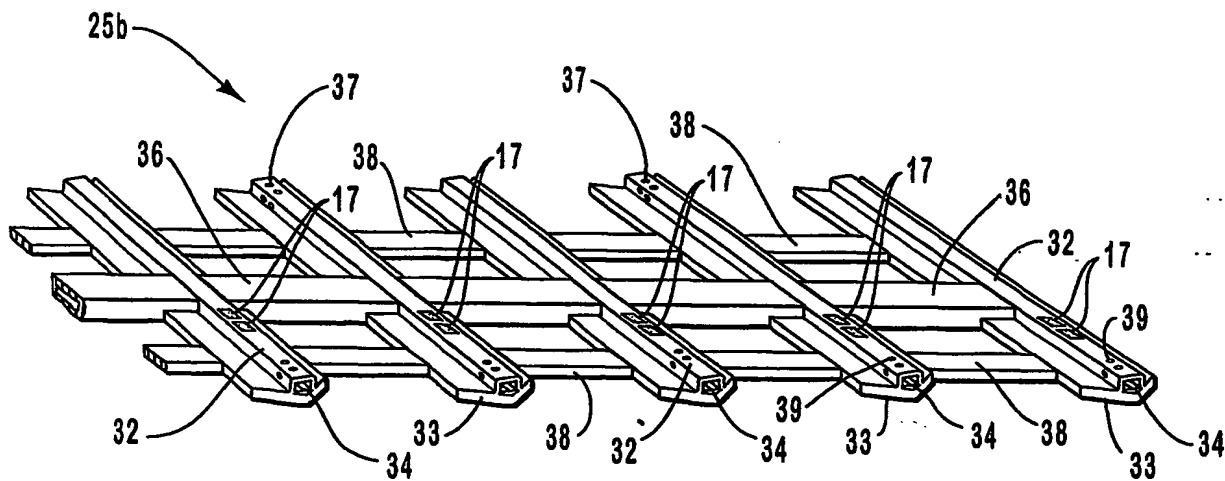


FIG. 4

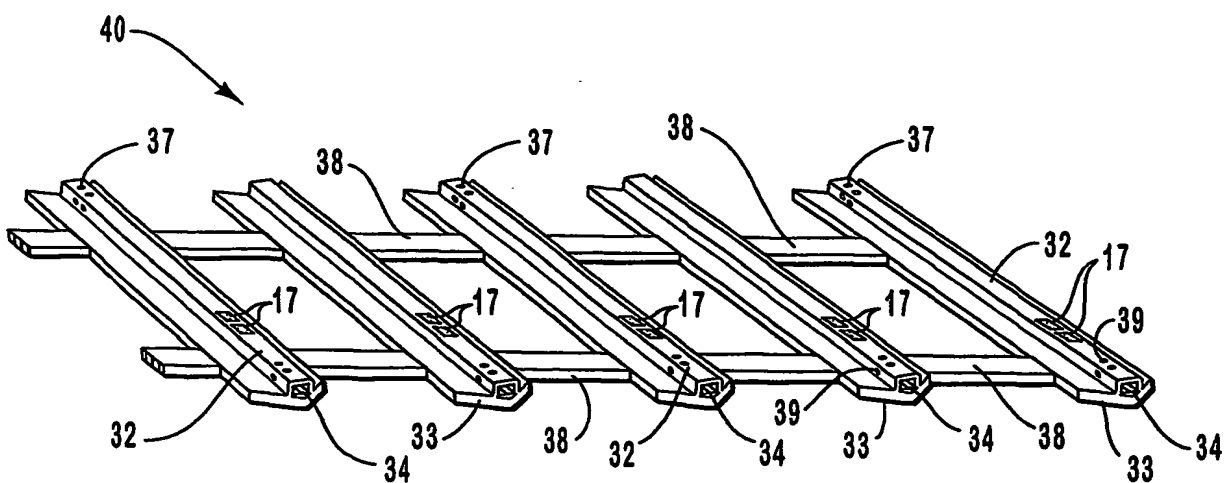


FIG. 5

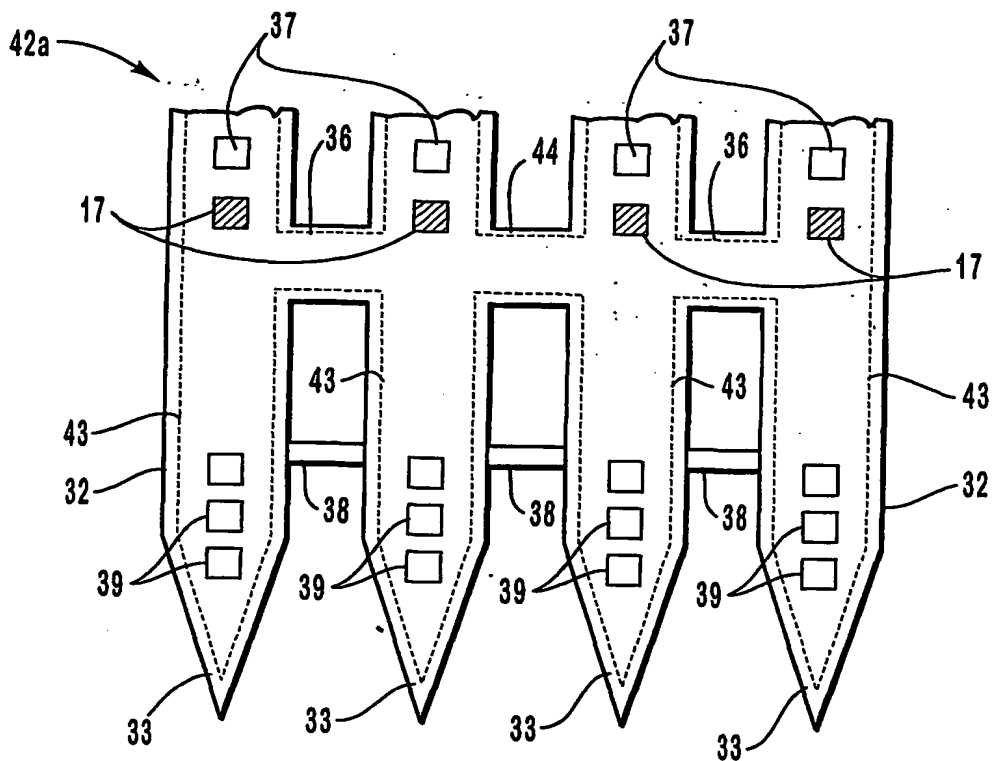


FIG. 6A

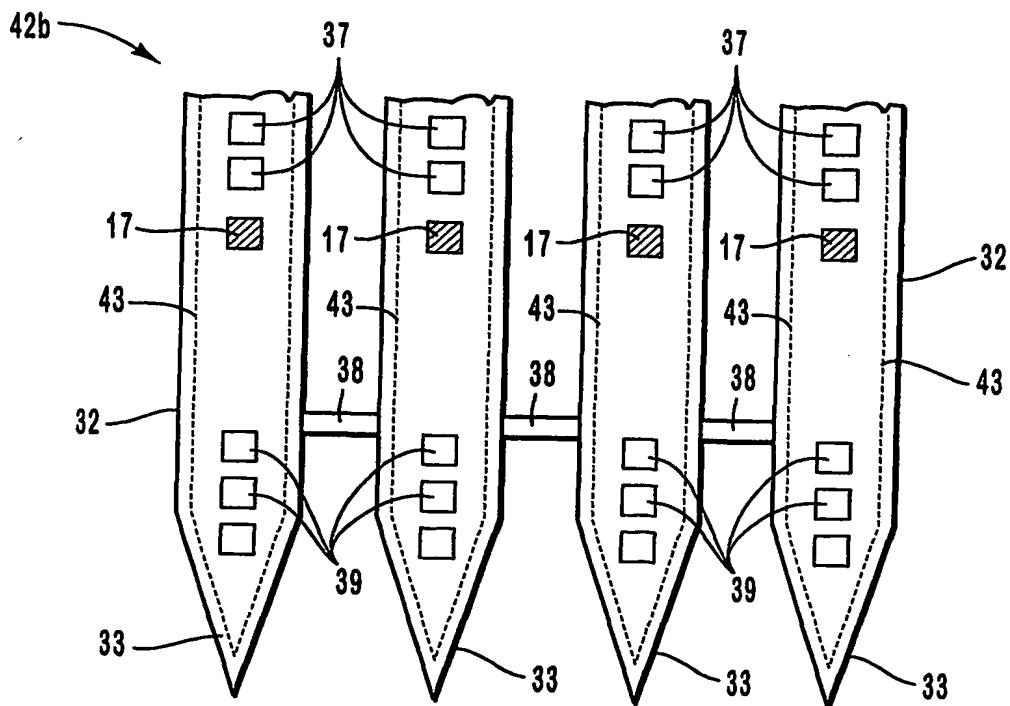


FIG. 6B

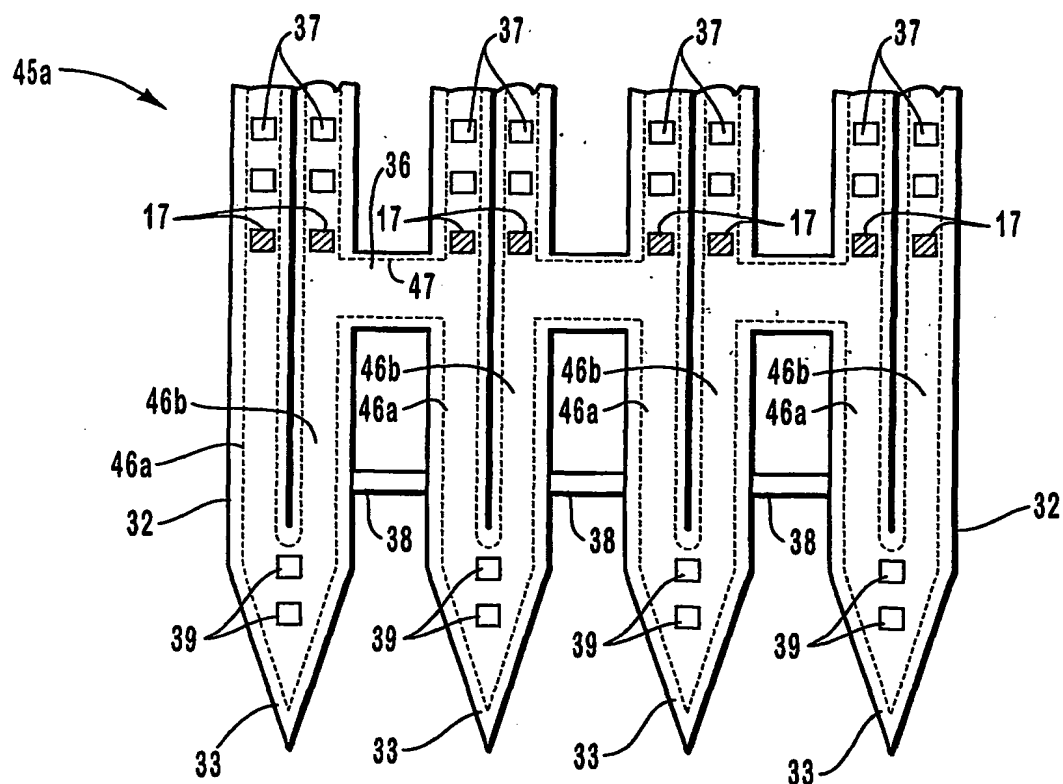


FIG. 7A

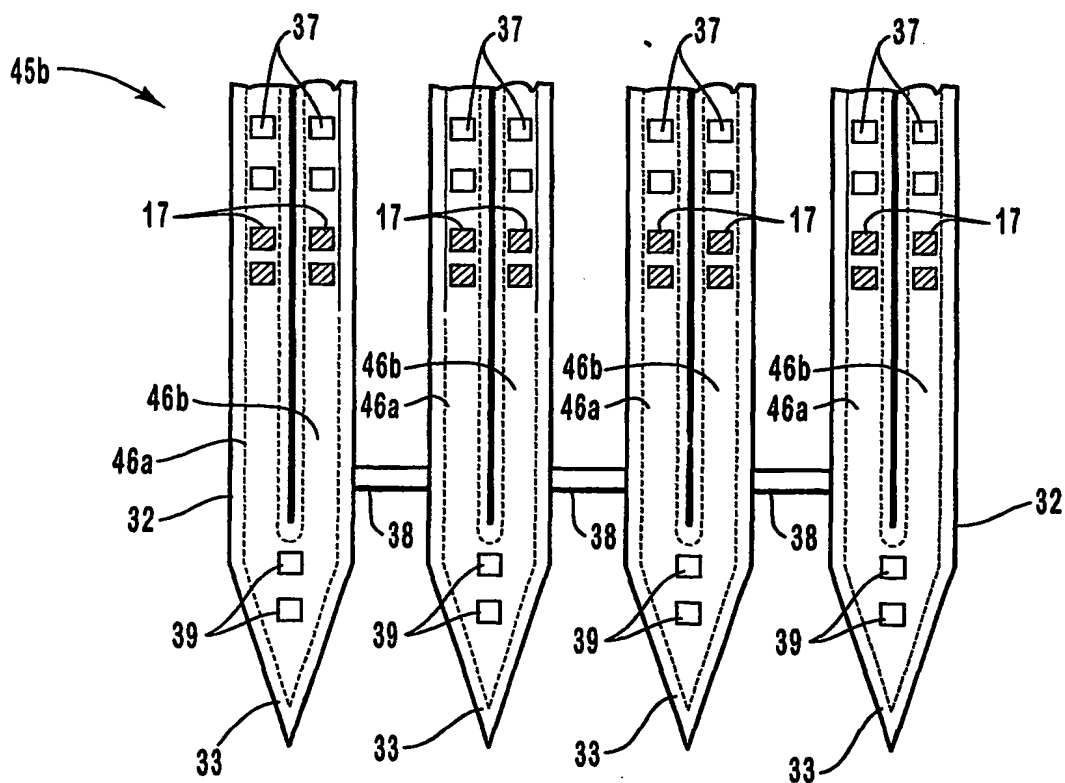


FIG. 7B

6 / 10

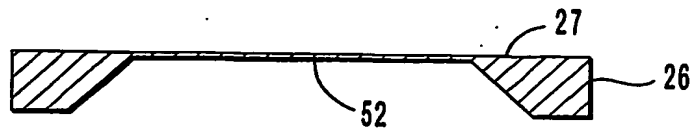


FIG. 8A

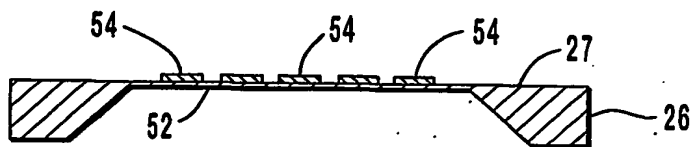


FIG. 8B

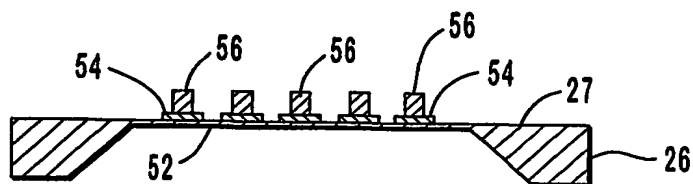


FIG. 8C

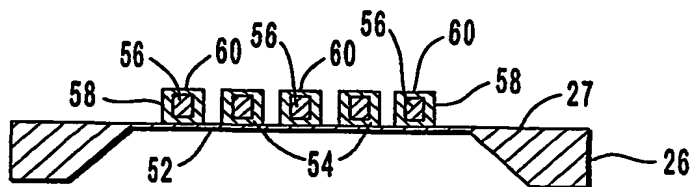


FIG. 8D

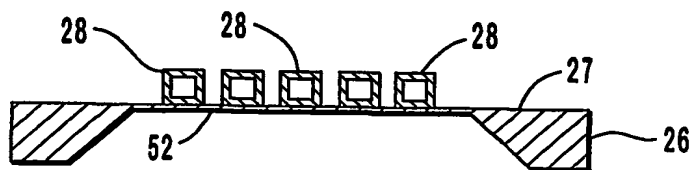


FIG. 8E

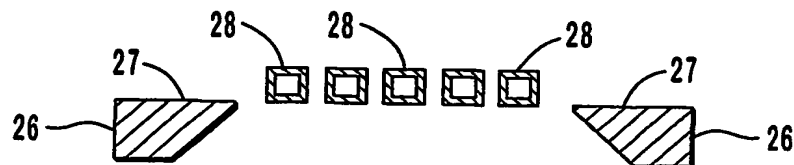


FIG. 8F

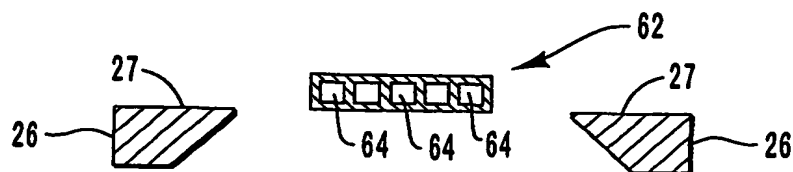
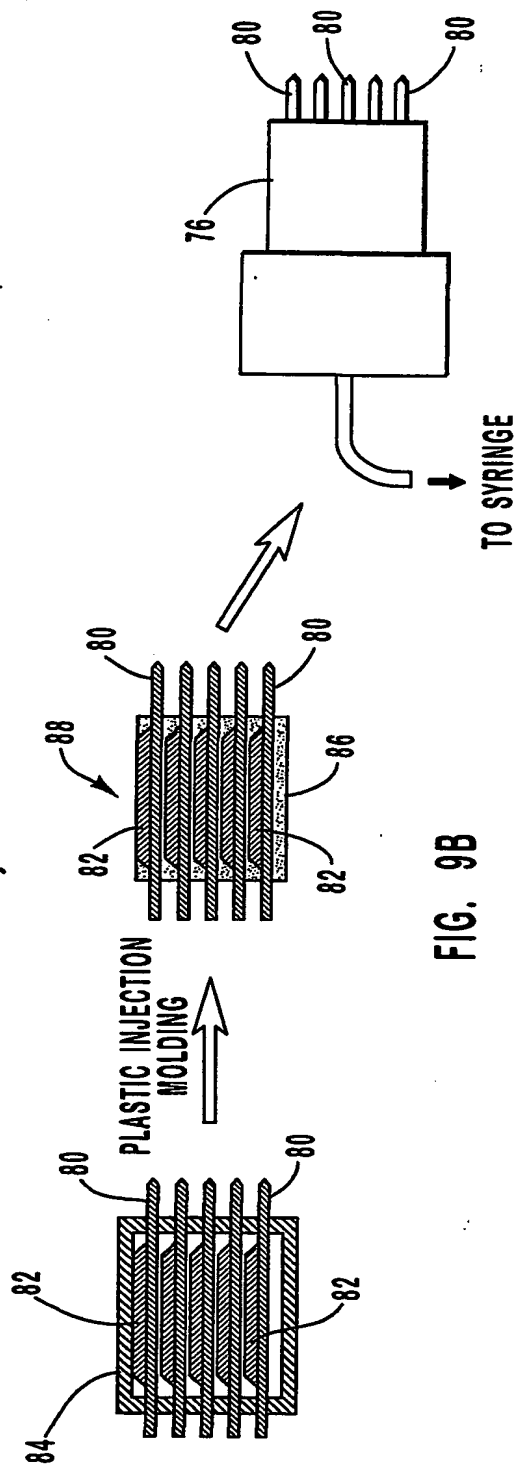
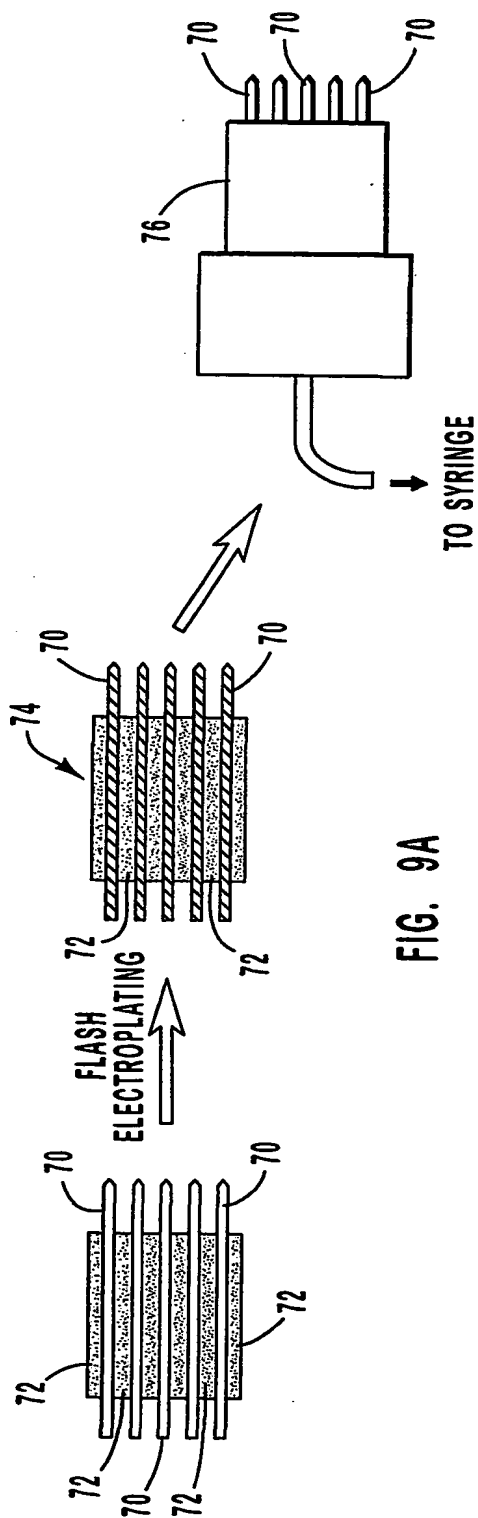


FIG. 8G





8 / 10

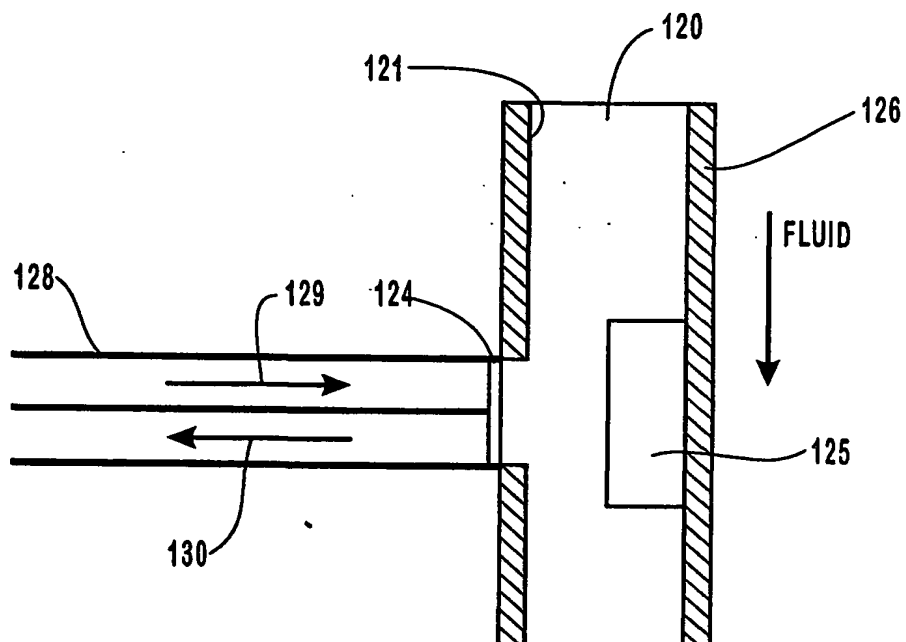


FIG. 10

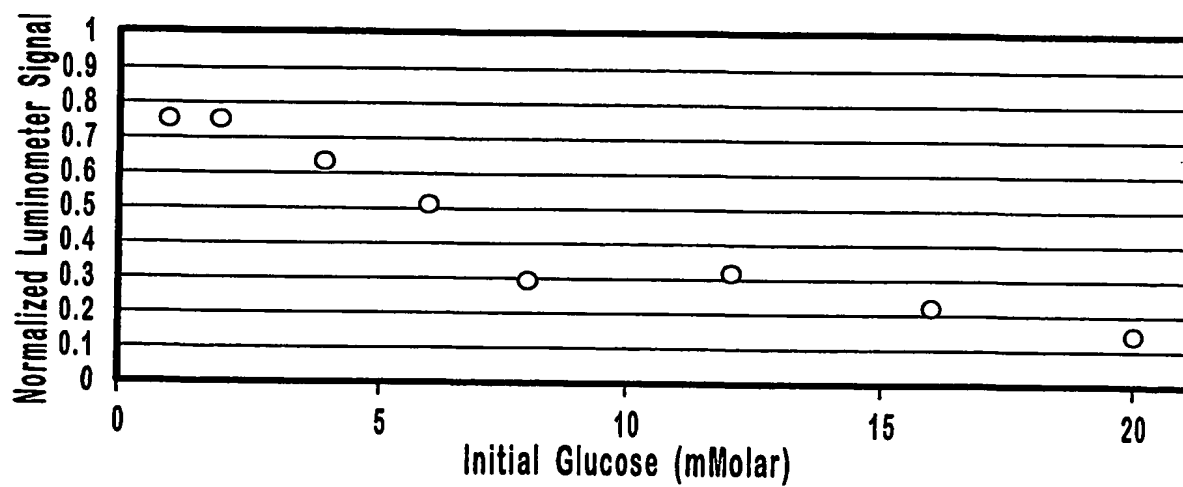


FIG. 11

9 / 10

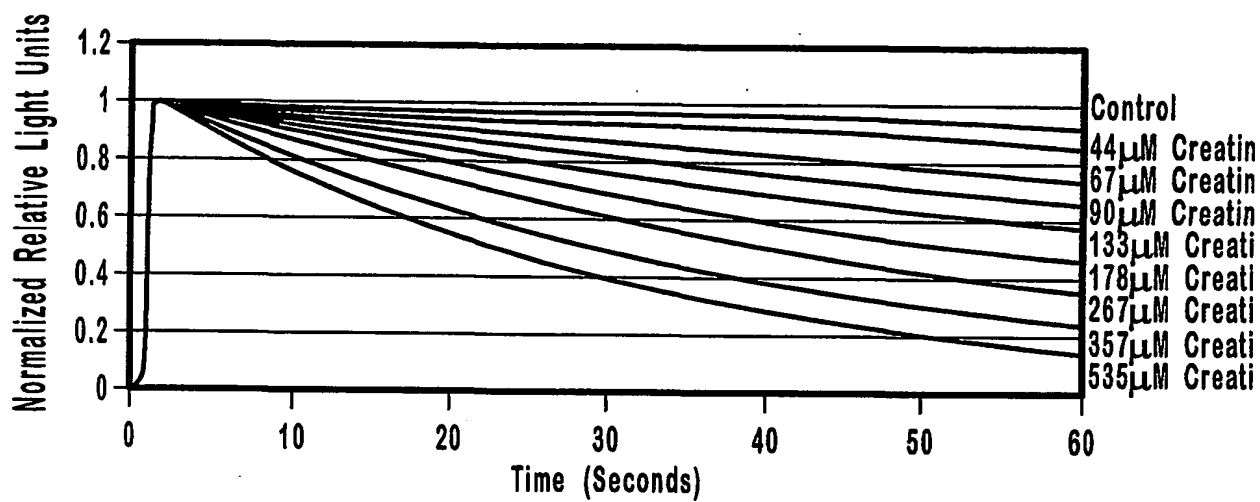


FIG. 12

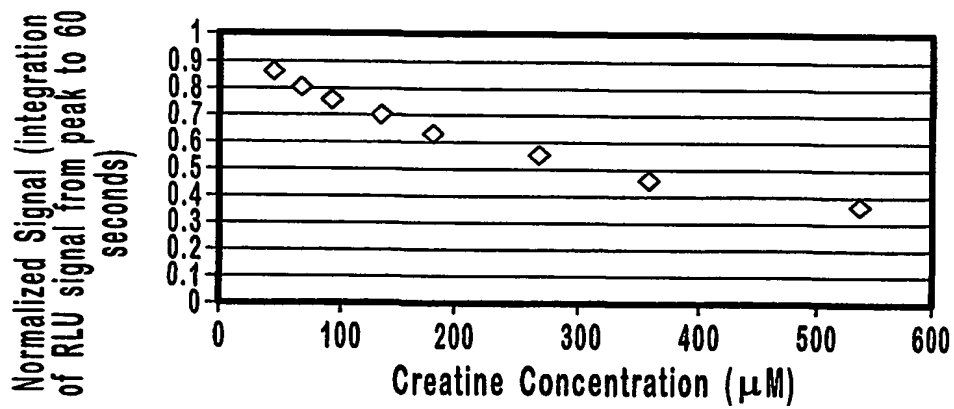


FIG. 13

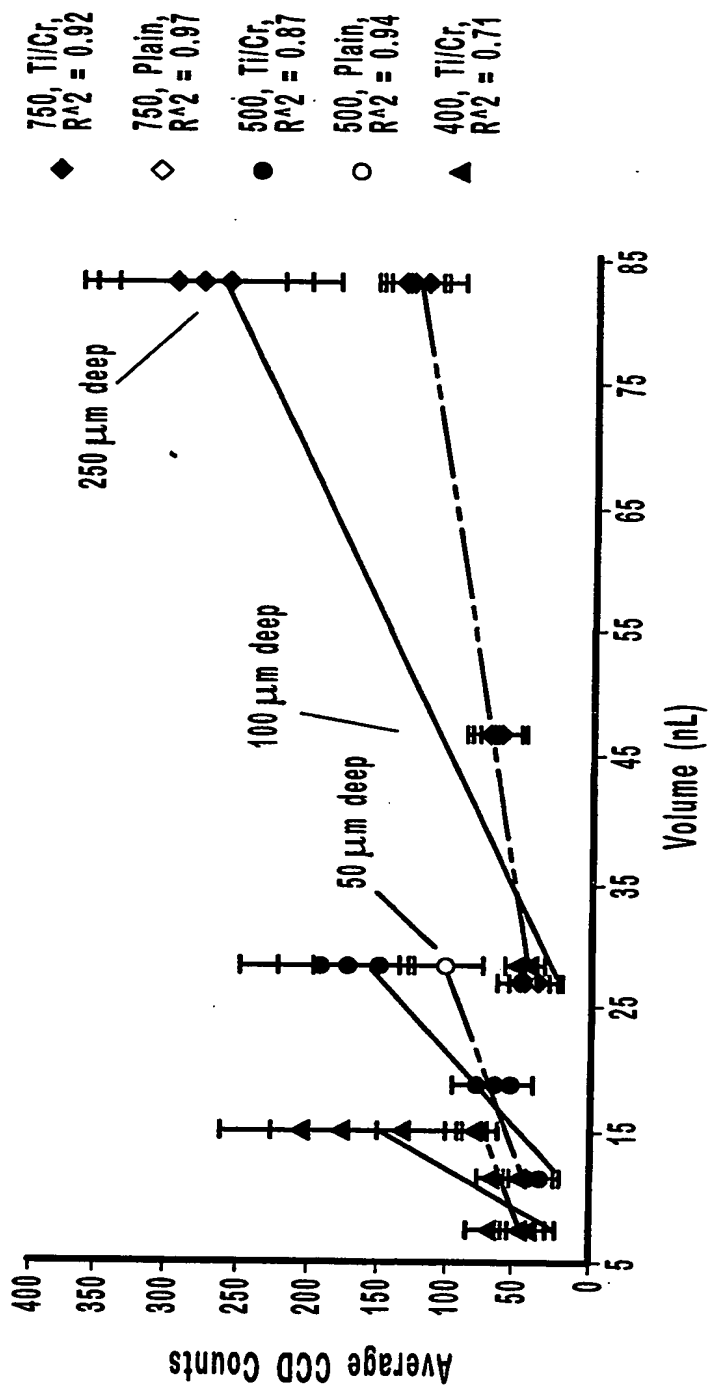


FIG. 14

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US01/17838

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : A61M 5/32

US CL : 604/272

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 604/21, 65, 66, 503, 506, 264, 272-273, 600/222-224, 181

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,484,399 A (DIRESTA et al) 16 January 1996, entire document.	1, 2, 4, 5, 8, 12, 63
X	US 6,009,347 A (HOFMANN) 28 December 1999, entire document.	1, 2, 4, 5, 9, 12, 63
A	US 5,591,139 A (LIN et al) 7 January 1997, entire document.	22-57, 65
A	US 5,312,456 A (REED et al) 17 May 1994, entire document.	22-57, 65

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"I" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"A" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

24 JULY 2001

Date of mailing of the international search report

14 AUG 2001

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